SEDIMENTATION ON LOW ISLES REEF AND ITS RELATION TO CORAL GROWTH

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WITH SEVEN FIGURES IN THE TEXT AND THREE PLATES

CONTENTS

PART I.

By S. M. Marshall and A. P. Orr.

PART II.

By A. P. Orr.

PART III.

By S. M. Marshall and A. P. Orr.

PART I.—THE SEDIMENTS ON THE REEF.

A knowledge of the sedimentation on a coral reef is important both from the geographical and biological points of view. The movements of sediment play a large part in determining the shape and structure of reefs, and biologically the sediments are of importance from the point of view of coral growth. Very little has been done in the way of actual measurement of sedimentation on a coral reef. A few observations have been made by Mayor (1924) on the amount of sand removed in a month from a reef flat in normal weather with one gale. The average quantity of sand collected in barrels of 2 feet diameter was 21·7 lb. Various observers have noticed actual movement of particles over the reef and have described the distribution of sediments on a reef (Wood-Jones, 1912).

It was thought that some idea of the movements of sediment might be obtained by placing, at various positions on a reef, jars in which the sediment would collect. It was recognized that jars placed in this way would enable only a minimal estimate of the sedimentation to be made. In the first place, since jars were generally arranged so that the level of the tops coincided with the level of the top of the nearest growing coral, small movements of sediment could not be observed, and only particles carried as high as the top of the jar would be collected. Secondly, since the jars were only collected at intervals of a week, very light sediment might well be stirred up again and so lost. To test the importance of the first factor, jars were sunk to nearly sand level close by jars A, B and C (see below) on one occasion and the difference in sediment measured (see p. 111). To avoid as far as possible error due to the second factor, deep jars were chosen so that it would require considerable disturbance to lift even fine sediment out of them. These sources of error will be dealt with later.

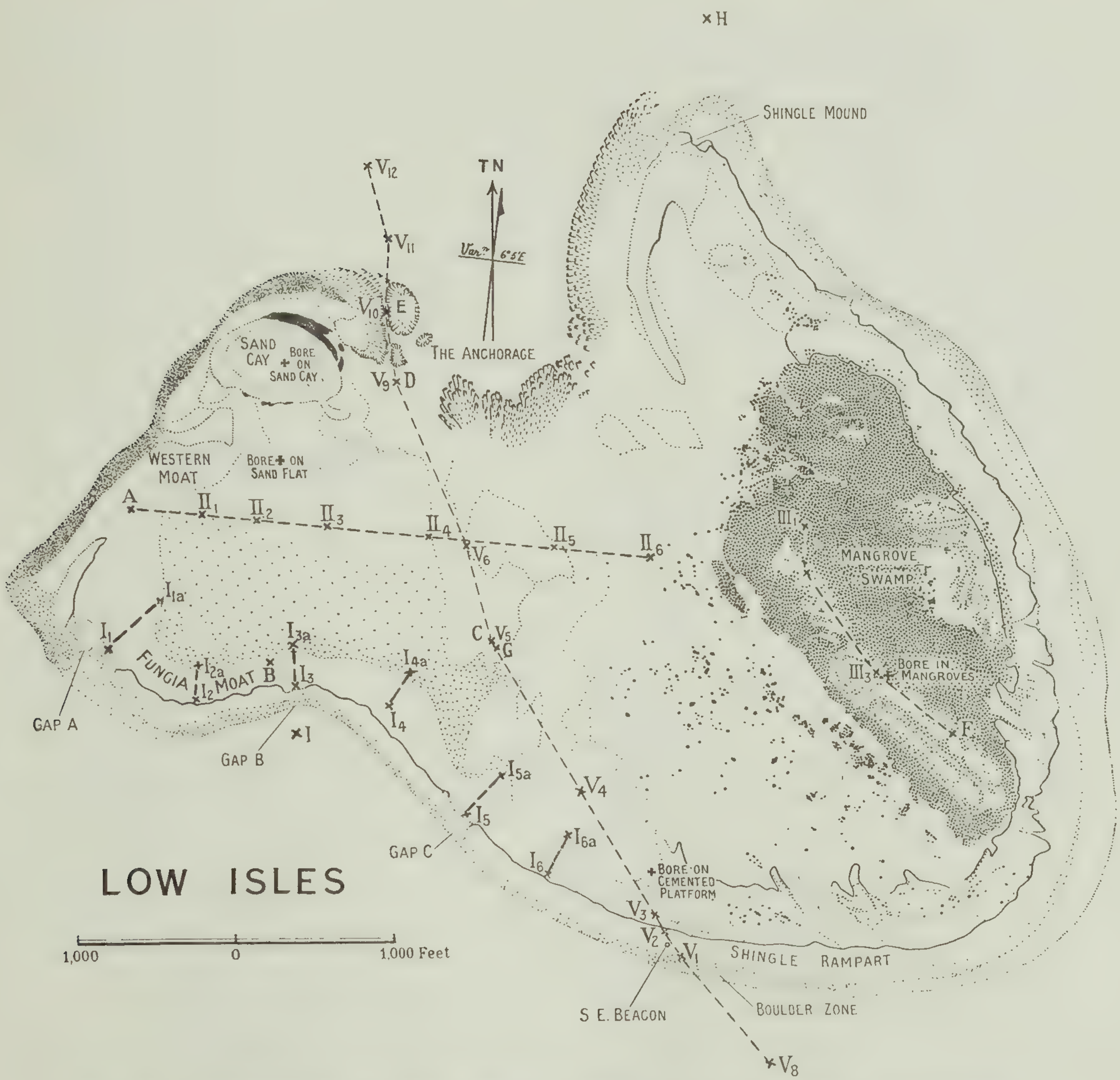
The jars used (see Plate II, 7) in the following experiments were 24 cm. high, the diameter at the top being $7\frac{1}{2}$ cm. and the area of the opening 44 sq. cm. They were fixed in position either by making them fast to short posts (in the case of jars in shallow water), or by fixing them to posts on cement blocks (in the case of jars in deeper water). It was found that an easily measured amount of sediment was generally collected in a week, and, as with longer intervals fine material might be lost, weekly collections were made throughout. The sediments were filtered off, well washed with distilled water, dried at 100° C. and weighed.

The jars were first exposed in December, the middle of the calmer summer period, and consecutive exposures were made till June, which is about the middle of the winter, or period of the S.E. trade wind. This wind blows for about eight months of the year at an average speed of 12 to 15 miles per hour. During the summer four months (November–February) there are calm periods alternating with windy periods, during which the wind may come from any direction. The wind forces during the course of these experiments are shown in Text-fig. 3 (*a*) and (*b*), and Table I.

During the whole of the experimental period jars were exposed in five positions each week, while towards the end various series of jars were exposed to measure sedimentation in particular localities. The position of the five jars is shown in Text-fig. 1 (A–E). A description of the surface features of the reef is given elsewhere in these reports in a paper by

Stephenson, Tandy and Spender, and the relation of the positions of the jars to these surface features can be inferred from the following descriptions:

A. In a sandy pool among growing coral in the Western Moat. The top of this jar was 38 cm. above sand level and was at the same height as the top of growing coral. At



TEXT-FIG. 1.—Sketch map of Low Isles based on the survey by M. A. Spender showing position of sediment jars and bores.

low spring tides the top of this jar was exposed 2–3 cm. for several hours. The depth below mean sea-level was 60 cm.

B. Near the Gap B at the eastern end of the Fungia Moat among growing coral. The top of the jar was 30 cm. above sand-level and was at the same height as the top of the nearest growing coral. At low spring tides the top of this jar was exposed 2–3 cm. for several hours. The depth below mean sea-level was 53 cm.

C. A few yards north of the oyster pen where coral is scarce. The top of the jar was 27 cm. above sand-level and was above the level of living coral. At the lowest spring tides the top of the jar may be exposed 2–3 cm. This jar was at a slightly lower level than A or B.

D. In the anchorage at a depth of 1·8 m. below mean sea-level. The top of the jar was 25 cm. above sand-level. No living coral was very near, but the top of the jar was well below the level of the nearest. This jar was never exposed at low tide.

E. In the anchorage in a sandy passage between two large rich patches of living coral at a depth of 3·6 m. below mean sea-level. The level of the top of the jar was well above the lowest living coral but one or two metres below the level of the top of living coral. The top of the jar was 58 cm. above sand-level.

These five positions were chosen so as to measure sedimentation among growing coral near the south-east edge, on the sand flat and to the north of the island in the anchorage.

TABLE I.

Date.	Average wind velocity in miles per hour.
Week ending Dec. 16	12·6
,, ,, ,, 23	5·4
,, ,, ,, 30	7·1
,, ,, Jan. 6	14·2
,, ,, ,, 13	9·6
,, ,, ,, 20	3·8
,, ,, ,, 27	7·4
,, ,, Feb. 3	6·7
,, ,, ,, 10	9·0
,, ,, ,, 17	2·3
,, ,, ,, 24	3·4
,, ,, Mar. 3	9·8
,, ,, ,, 10	5·6
,, ,, ,, 17	15·9
,, ,, ,, 24	13·8
,, ,, ,, 31	10·0
,, ,, April 7	8·6
,, ,, ,, 14	14·1
,, ,, ,, 21	16·6
,, ,, ,, 28	8·5
,, ,, May 5	15·3
,, ,, ,, 12	15·2
,, ,, ,, 19	11·8
,, ,, ,, 26	12·0
,, ,, June 2	11·5

TABLE II.

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
A	Out 9.xii.28 In 16.xii.28	7	6·1	..	..	1·1	0·1	2·7	7·0	88·4
B	Out 9.xii.28 In 16.xii.28	7	15·8	..	..	1·5	3·6	15·1	29·2	50·6
C	Out 10.xii.28 In 17.xii.28	7	3·5	..	..	..	..	..	0·1	99·9
D	Out 11.xii.28 In 16.xii.28	5	3·3	..	..	3·1*	1·6	7·7	31·0	56·7
A	Out 16.xii.28 In 23.xii.28	7	1·6	..	..	..	..	6·5	13·0	80·6
B	Out 16.xii.28 In 23·xii.28	7	1·3	..	..	..	..	..	3·3	96·7
C	Out 17.xii.28 In 23.xii.28	6	0·7	..	..	..	..	..	1·5	98·5
D	Out 16.xii.28 In 23.xii.28	7	0·8	..	..	..	..	..	1·6	98·4
E	Out 18.xii.28 In 23.xii.28	5	0·8	..	..	..	..	..	4·1	96·0
A	Out 23.xii.28 In 30.xii.28	7	8·3	..	..	2·6	1·1	2·2	7·3	86·8
B	Out 23.xii.28 In 30.xii.28	7	23·2	3·0	3·1	4·5	9·1	20·9	33·1	26·2
C	Out 23.xii.28 In 30.xii.28	7	3·6	..	..	..	..	0·6	0·6	98·9
D	Out 23.xii.28 In 30.xii.28	7	2·2	..	..	..	..	1·1	3·7	95·2
E	Out 23.xii.28 In 30.xii.28	7	2·3	..	..	..	5·3*	1·0	2·9	90·9
A	Out 30.xii.28 In 7.i.29	8	24·6	0·8	0·6	2·2	2·8	9·6	20·8	63·4
B	Out 30.xii.28 In 7.i.29	8	173.9	5·8	4·1	7·2	12·5	27·3	27·5	15·8
C	Out 30.xii.28 In 7.i.29	8	3·8	..	..	..	..	..	1·1	98·9
D	Out 30.xii.28 In 8.i.29	9	9·8	..	..	..	..	3·1	3·4	93·5
E	Out.30.xii.28 In 8.i.29	9	8·9	..	..	..	..	..	1·2	98·8
A	Out 7.i.29 In 13.i.29	6	14·7	..	..	2·1	2·0	6·2	18·4	71·4
B	Out 7.i.29 In 13.i.29	6	81·5	4·9	3·9	7·5	14·3	30·9	29·3	9·1
C	Out 7.i.29 In 13.i.29	6	2·8	..	..	2·6	0·6	0·7	1·5	94·7

* Includes one or more gastropods.

TABLE II (*continued*).

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
D	Out 8.i.29 In 13.i.29	5	11·1	..	..	..	1·2	0·6	1·0	97·3
E	Out 8.i.29 In 13.i.29	5	20·9	..	..	..	..	0·1	0·3	99·6
A	Out 13.i.29 In 20.i.29	7	3·1	..	..	..	..	..	3·8	96·2
B	Out 13.i.29 In 20.i.29	7	0·5	..	..	..	..	..	4·9	95·1
C	Out 13.i.29 In 20.i.29	7	1·3	..	..	..	..	..	1·6	98·4
D	Out 13.i.29 In 20.i.29	7	2·1	..	..	..	..	..	7·6	92·4
E	Out 13.i.29 In 20.i.29	7	2·7	..	..	..	..	..	0·4	99·6
A	Out 20.i.29 In 27.i.29	7	7·7	..	..	2·3	2·2	4·3	16·5	74·7
B	Out 20.i.29 In 27.i.29	7	32·5	2·0	1·9	3·5	9·1	24·3	37·2	22·0
C	Out 20.i.29 In 27.i.29	7	2·1	..	..	..	2·5	3·0	4·0	90·4
D	Out 20.i.29 In 27.i.29	7	3·2	..	..	..	6·6	4·3	8·9	80·3
E	Out 20.i.29 In 27.i.29	7	4·1	..	..	..	..	..	2·1	97·9
A	Out 27.i.29 In 3.ii.29	7	2·7	..	..	..	..	..	9·4	90·6
B	Out 27.i.29 In 3.ii.29	7	4·8	..	..	..	3·7	5·4	14·3	76·6
C	Out 27.i.29 In 3.ii.29	7	1·2	..	..	..	..	0·9	0·9	98·1
D	Out 27.i.29 In 3.ii.29	7	1·2	..	..	..	..	..	3·5	96·5
E	Out 27.i.29 In 3.ii.29	7	1·7	..	..	..	..	..	1·8	98·2
F	Out 24.i.29 In 3.ii.29	10	5·0	..	..	..	..	..	..	..
A	Out 3.ii.29 In 10.ii.29	7	8·2	..	..	2·9	1·8	6·0	11·8	77·6
B	Out 3.ii.29 In 10.ii.29	7	54·4	2·9	2·7	4·7	10·2	33·0	28·1	18·5
C	Out 3.ii.29 In 10.ii.29	7	4·3	..	..	..	1·7	0·5	2·7	95·1
D	Out 3.ii.29 In 10.ii.29	7	3·4	..	..	..	6·1	1·3	6·5	86·1
E	Out 3.ii.29 In 10.ii.29	7	4·0	..	..	..	..	..	2·8	97·2

TABLE II (*continued*).

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	$2\frac{1}{2}$–3 mm.	2–$2\frac{1}{2}$ mm.	$1\frac{1}{2}$–2 mm.	1–$1\frac{1}{2}$ mm.	$\frac{1}{2}$–1 mm.	< $\frac{1}{2}$ mm.
F	Out 3.ii.29 In 10.ii.29	7	2·1	..	..	..	..	..	..	..
H	Out 2.ii.29 In 9.ii.29	7	2·8	10·4*	..	..	..	1·1	1·5	87·0
I	Out 2.ii.29 In 9.ii.29	7	12·7	..	..	..	0·6	1·1	4·5	93·8
A	Out 10.ii.29 In 17.ii.29	7	2·3	..	..	..	..	4·1	5·4	90·4
B	Out 10.ii.29 In 17.ii.29	7	0·2	..	..	..	..	..	5·7	94·3
C	Out 10.ii.29 In 17.ii.29	7	1·0	..	..	..	..	..	17·9	82·1
D	Out 10.ii.29 In 17.ii.29	7	1·6	..	..	..	..	3·3	6·7	90·0
E	Out 10.ii.29 In 17.ii.29	7	2·0	..	..	..	..	..	5·9	94·1
F	Out 10.ii.29 In 17.ii.29	7	1·5	..	..	..	..	..	2·1	97·9
H	Out 9.ii.29 In 16.ii.29	7	0·7	..	..	..	..	..	1·6	98·4
I	Out 9.ii.29 In 16.ii.29	7	0·3	..	..	..	..	..	1·9	98·1
A	Out 17.ii.29 In 24.ii.29	7	1·6	..	..	..	1·4	1·4	2·1	95·2
B	Out 17.ii.29 In 24.ii.29	7	2·3	..	2·4	1·9	2·9	7·1	18·1	67·6
C	Out 17.ii.29 In 24.ii.29	7	2·1	16·9*	4·2	2·1	1·6	4·8	7·4	63·0
D	Out 17.ii.29 In 24.ii.29	7	1·7	..	..	..	2·6	2·6	4·5	90·4
E	Out 17.ii.29 In 24.ii.29	7	2·6	..	..	..	..	..	3·8	96·2
F	Out 17.ii.29 In 24.ii.29	7	2·8	..	..	..	..	..	..	..
H	Out 16.ii.29 In 23.ii.29	7	0·8	..	..	..	..	..	1·3	98·7
I	Out 16.ii.29 In 23.ii.29	7	<1·0	..	..	..	..	..	..	..
A	Out 24.ii.29 In 3.iii.29	7	37·4	..	..	2·3	1·4	4·7	13·9	77·8
B	Out 24.ii.29 In 3.iii.29	7	173.3	4·1	3·1	5·3	10·0	25·8	38·1	13·7
C	Out 24.ii.29 In 3.iii.29	7	24·2	..	..	..	..	..	..	..
D	Out 24.ii.29 In 3.iii.29	7	46·2	..	..	..	..	0·3	0·5	99·2

* Includes one or more gastropods.

TABLE II (*continued*).

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
E	Out 24.ii.29 In 3.iii.29	7	59·9	..	..	..	0·1	0·6	0·6	98·8
F	Out 24.ii.29 In 3.iii.29	7	3·4	..	..	..	..	3·0	1·0	96·0
H	Out 23.ii.29 In 4.iii.29	9	19·8	..	..	..	2·0	2·0	5·7	90·2
I	Out 23.ii.29 In 2.iii.29	7	35·3	..	0·3	0·3	0·7	0·5	18·5	79·7
A	Out 3.iii.29 In 10.iii.29	7	4·8	..	..	..	0·9	0·2	3·7	95·1
B	Out 3.iii.29 In 10.iii.29	7	5·6	..	..	3·0	3·6	12·2	27·1	54·1
C	Out 3.iii.29 In 10.iii.29	7	4·9	..	..	..	1·6	0·7	1·4	96·4
D	Out 3.iii.29 In 10.iii.29	7	Lost	..	..	..	..	..	..	..
E	Out 3.iii.29 In 10.iii.29	7	8·0	..	..	..	..	..	1·9*	98·1
F	Out 3.iii.29 In 10.iii.29	7	1·6	..	..	..	..	..	..	..
H	Out 4.iii.29 In 17.iii.29	13	7·0	..	..	..	..	..	0·9	99·1
I	Out 2.iii.29 In 31.iii.29	29	25·6	..	..	..	..	..	0·3	99·7
A	Out 10.iii.29 In 17.iii.29	7	20·3	..	..	..	1·6	2·8	7·7	87·9
B	Out 10.iii.29 In 17.iii.29	7	277.2	6·3	4·0	7·5	13·0	29·8	31·3	8·3
C	Out 10.iii.29 In 17.iii.29	7	7·1	..	..	..	4·5	4·5	4·1	86·9
D	Out 10.iii.29 In 17.iii.29	7	9·1	..	..	..	..	1·4	1·3	97·4
E	Out 10.iii.29 In 17.iii.29	7	7·4	..	..	..	..	0·6	0·6	98·8
F	Out 10.iii.29 In 17.iii.29	7	3·5	..	..	..	..	..	2·7	97·3
A	Out 17.iii.29 In 24.iii.29	7	10·1	..	..	..	2·5	6·6	9·2	81·7
B	Out 17.iii.29 In 24.iii.29	7	155·1	4·1	2·9	6·0	6·7	31·3	38·2	10·8
C	Out 17.iii.29 In 24.iii.29	7	10·7	..	..	..	7·9	5·0	12·5	74·6
D	Out 17.iii.29 In 24.iii.29	7	1·5	..	..	..	8·5	6·2	9·3	76·0

* Includes one or more gastropods.

TABLE II (*continued*).

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
E	Out 17.iii.29 In 24.iii.29	7	5·6	..	..	..	..	..	1·2	98·8
F	Out 17.iii.29 In 24.iii.29	7	4·1	..	..	..	..	..	..	..
A	Out 24.iii.29 In 31.iii.29	7	2·4	..	..	..	..	..	1·7	98·3
B	Out 24.iii.29 In 31.iii.29	7	48·3	2·9	2·4	5·1	10·5	27·0	35·4	16·7
C	Out 24.iii.29 In 31.iii.29	7	2·1	..	..	..	..	..	6·7*	93·3
D	Out 24.iii.29 In 31.iii.29	7	1·1	..	..	..	..	..	11·2	88·8
E	Out 24.iii.29 In 31.iii.29	7	2·5	..	..	..	..	..	1·5	98·5
F	Out 24.iii.29 In 31.iii.29	7	1·3	..	..	..	..	..	..	..
A	Out 31.iii.29 In 7.iv.29	7	9·7	..	..	..	0·6	0·4	1·3	97·7
B	Out 31.iii.29 In 7.iv.29	7	33·7	1·8	1·8	3·5	8·4	25·4	39·7	19·5
C	Out 31.iii.29 In 7.iv.29	7	9·7	..	..	1·2	0·3	0·9	5·1	92·4
D	Out 31.iii.29 In 7.iv.29	7	16·6	..	..	..	0·2	0·3	1·8	97·8
E	Out 31.iii.29 In 7.iv.29	7	28·0	..	..	..	..	..	0·3	99·7
F	Out 31.iii.29 In 7.iv.29	7	1·0	..	..	..	..	..	..	..
A	Out 7.iv.29 In 14.iv.29	7	6·1	..	..	..	..	2·1	3·6	94·3
B	Out 7 iv.29 In 14.iv.29	7	32·9	0·8	1·2	2·3	4·8	18·5	40·1	32·4
C	Out 7.iv.29 In 14.iv.29	7	4·1	..	..	..	..	..	1·0	99·0
D	Out 7.iv.29 In 14.iv.29	7	0·7	..	..	..	..	..	14·3	85·7
E	Out 7.iv.29 In 14.iv.29	7	2·7	..	..	..	..	..	7·6	92·4
F	Out 7.iv.29 In 14.iv.29	7	1·4	..	..	..	..	..	..	..
A	Out 14.iv.29 In 21.iv.29	7	14·2	..	..	1·7	1·3	3·8	12·8	80·5
B	Out 14.iv.29 In 21.iv.29	7	113·0	3·9	3·2	6·1	12·0	26·5	36·4	11·9

* Includes one or more gastropods.

TABLE II (*continued*).

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
C	Out 14.iv.29 In 21.iv.29	7	9·3	..	..	..	1·5	2·1	3·4	93·0
D	Out 14.iv.29 In 21.iv.29	7	5·4	..	..	..	4·9	3·5	4·6	87·0
E	Out 14.iv.29 In 21.iv.29	7	4·8	..	..	..	..	..	6·5	93·6
F	Out 14.iv.29 In 21.iv.29	7	2·1	..	..	..	..	..	..	..
A	Out 21.iv.29 In 28.iv.29	7	2·5	..	..	..	..	3·1	4·9	92·0
B	Out 21.iv.29 In 28.iv.29	7	23·8	2·2	1·9	4·1	9·1	22·4	30·6	29·8
C	Out 21.iv.29 In 28.iv.29	7	2·0	..	..	..	..	4·4	1·7	93·9
D	Out 21.iv.29 In 28.iv.29	7	1·7	..	..	..	..	12·8	7·8	79·4
E	Out 21.iv.29 In 28.iv.29	7	2·8	..	..	..	..	3·2	3·2	93·6
A	Out 28.iv.29 In 5.v.29	7	6·4	..	..	2·0	1·1	3·1	9·0	84·8
B	Out 28.iv.29 In 5.v.29	7	41·8	1·7	1·8	3·6	7·1	21·6	38·4	25·7
C	Out 28.iv.29 In 5.v.29	7	4·6	..	..	..	1·8	0·7	0·9	96·5
D	Out 28.iv.29 In 5.v.29	7	3·0	..	..	..	15·1	1·6	1·2	82·2
E	Out 28.iv.29 In 5.v.29	7	3·2	..	..	..	..	..	9·6	90·4
A	Out 5.v.29 In 12.v.29	7	8·4	..	..	..	..	..	..	..
B	Out 5.v.29 In 12.v.29	7	42·4	..	..	..	..	..	..	..
C	Out 5.v.29 In 12.v.29	7	5·1	..	..	..	..	..	..	..
D	Out 5.v.29 In 12.v.29	7	4·1	..	..	..	..	..	..	..
E	Out 5.v.29 In 12.v.29	7	3·8	..	..	..	..	..	..	..
A	Out 12.v.29 In 19.v.29	7	4·1	..	..	0·5	0·8	3·4	13·7	81·6
B	Out 12.v.29 In 19.v.29	7	13·1	1·3	1·2	4·0	7·1	21·7	33·3	31·5
C	Out 12.v.29 In 19.v.29	7	3·3	..	..	..	1·7	0·3	2·0	95·9

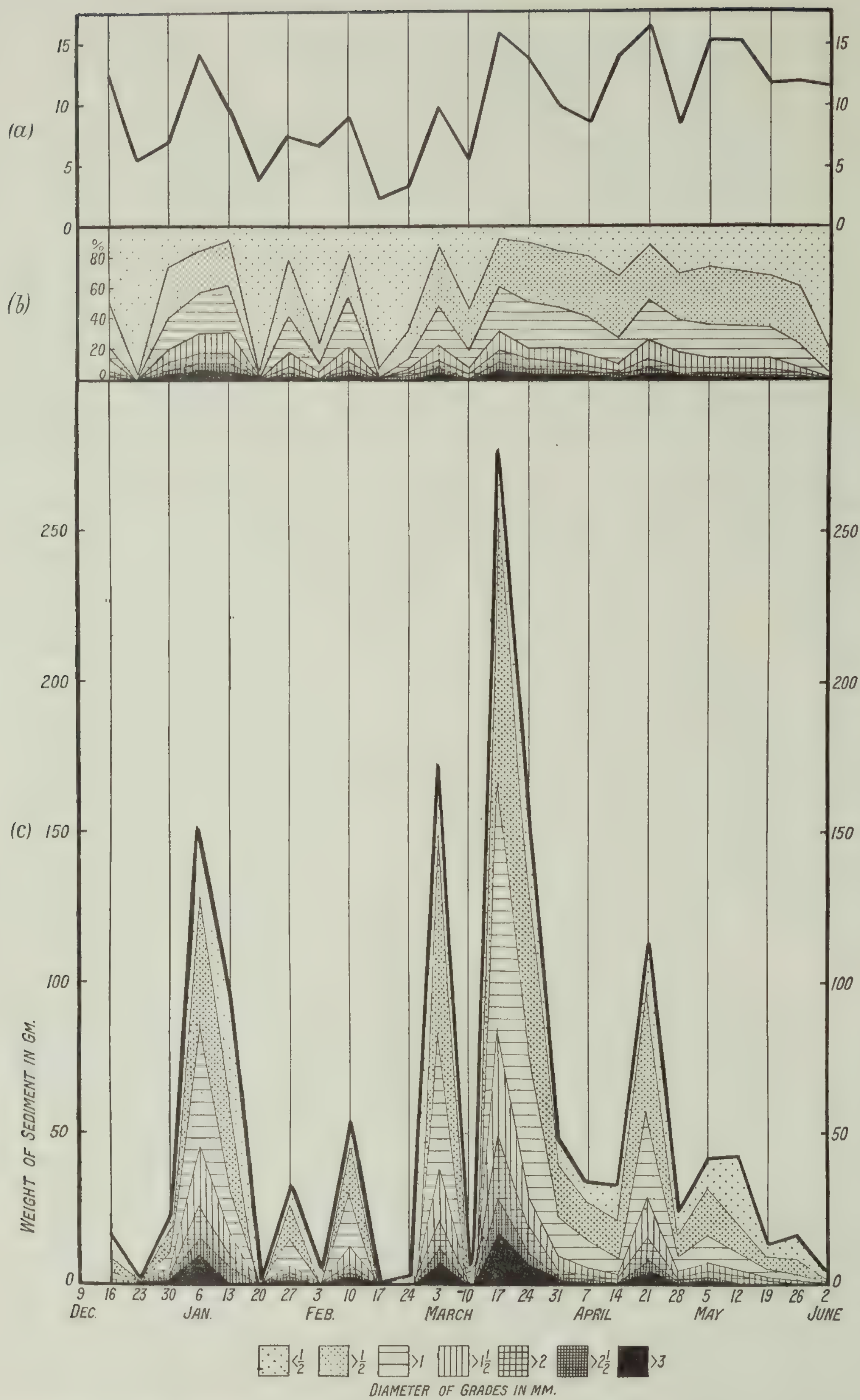
* Includes one or more gastropods.

TABLE II (*continued*).

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
D	Out 12.v.29 In 19.v.29	7	1·7	..	..	..	2·2	4·3	15·8	77·7
E	Out 12.v.29 In 19.v.29	7	2·6	..	..	..	..	..	8·6	91·4
A	Out 19.v.29 In 26.v.29	7	3·5	..	..	..	..	1·8	3·3	94·9
B	Out 19.v.29 In 26.v.29	7	16·3	1·4	0·8	1·9	4·0	14·8	37·6	39·5
C	Out 19.v.29 In 26.v.29	7	2·7	..	..	..	..	..	0·4	99·6
D	Out 19.v.29 In 26.v.29	7	3·6	..	..	..	..	4·3	4·0	91·6
E	Out 19.v.29 In 26.v.29	7	2·8	..	..	..	..	..	..	..
A	Out 26.v.29 In 2.vi.29	7	1·0	..	..	..	1·1	1·1	1·1	96·7
B	Out 26.v.29 In 2.vi.29	7	3·9	..	..	..	1·6	4·4	13·9	80·1
C	Out 26.v.29 In 2.vi.29	7	1·2	..	..	..	..	2·0	1·0	97·0
D	Out 26.v.29 In 2.vi.29	7	1·5	..	..	..	..	3·8	3·0	93·2
E	Out 26.v.29 In 2.vi.29	7	1·4	..	..	..	..	..	2·3	97·7

THE QUANTITY OF THE SEDIMENTS.

The quantity of sediment collected in these five jars from week to week is shown in Text-figs. 2 and 3 and Table II. Full details of the wind records are given in the Hydrographic Report, Vol. II of these Reports. The average velocity of the wind for each week is shown in Text-fig. 3*b* and Table I, and the daily average wind force and direction are shown in Text-fig. 3*a*. This last figure has all the winds N. of the east-west line plotted with full values as N., and all winds S. of the east-west line plotted similarly as S. E. and W. winds are not shown on this figure, but as they were very infrequent the wind forces are not seriously misrepresented. The wind direction was read at 9 a.m. daily but in several cases there was a change in direction of the wind during the day. These changes are occasionally of importance in interpreting the results. Owing to the position of the anemometer north winds were inaccurately recorded, and the values shown for these ought generally to be much greater. On several occasions there was a hard N. wind during the afternoon when a different direction had been recorded at 9 a.m. In such cases a cross is marked on Text-fig. 3*a*. These winds are infrequent but they are very important. The representation of the winds as N. or S. is not so arbitrary as it seems at first sight, for the



TEXT-FIG. 2.—The relation of the wind to sediment collected at position B. (*a*) Average wind velocity per week. (*b*) Percentage of grades in the sediments at B. (*c*) Total amount of sediment in gm. and its grades at B. In cases where the jar was exposed for more or less than a week, the result has been calculated as for seven days.

winds marked S. were almost invariably S.E., E.S.E. or S.S.E., the important directions with respect to the configuration of the reef, and most N. winds attacked the reef on its unprotected side. Wind records were kept by Mr. A. G. Nicholls, to whom we are indebted for all the information given.

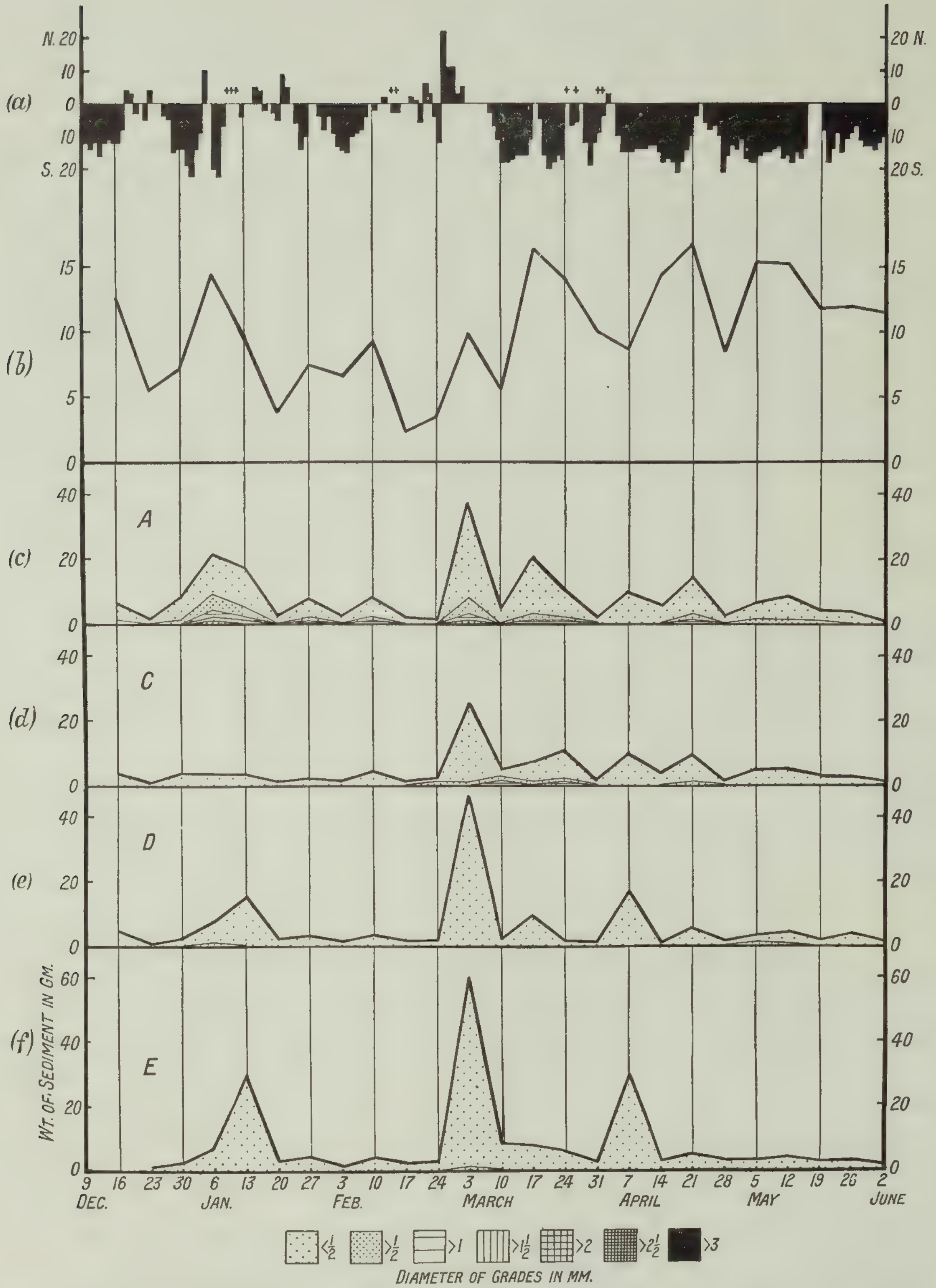
A comparison of the curve for average weekly wind velocity with the curve representing the quantity of sediment collected at B (Text-fig. 2(*c*)) shows that these are closely related. Peaks in the winds correspond with large amounts of sediment in the jar, the only discrepancy being from 7th to 14th April, when, with a small increase in wind, the quantity of sediment is unchanged. This, however, is to be explained by N. wind between the 31st March and 7th April, and, as will be seen later, a N. wind has a disproportionately great effect in moving sediment. The sediment from 31st March to 7th April is therefore higher than expected.

The quantity of sediment, however, is not accurately proportional to the wind velocity. Thus the peak of 24th February to 3rd March is higher than would be expected from the wind. while that of 14th to 21st April is lower. It is very probable that the height of the peak in the first case is caused by the N. wind at this time. The relatively small peak of 14th to 21st April may be because, occurring after a long, steady spell of S.E. wind, conditions were comparatively stable and little sediment was shifted. The comparative stability of conditions after the onset of the steady S.E. wind is shown in Text-fig. 2(*b*), which represents the percentages of the different grades collected. During the summer unstable period the percentages of the different grades collected were most erratic, but after the onset of the S.E. trade wind they were comparatively constant. The large peak of 10th to 17th March occurs shortly after a N. wind which disturbed the equilibrium on the reef, and this large quantity of sediment may represent a return to stable conditions.

The great increase in the quantity of sediment when the wind is relatively strong may be because a certain speed of water movement is required to lift particles of a definite size. If this were so, a long-continued wind of low velocity could not have the same effect as a wind of high velocity acting for a short time, since the latter would pass the critical velocity for moving sediment of a certain size while the former would not. This again will depend on the depth of the water, since, with the same wind, a small current will be generated in deep water and a strong current in shallow water. During the period of the S.E. trade wind the quantities of sediment were higher than during the calms of the summer months.

The quantity of sediment collected at B was much greater than that collected at any other position of the series. The explanation of this lies, not in its nearness to the S.E., and therefore exposed, part of the reef, but in a peculiarity in the conditions where it lay. It was situated in the moat, which is subject to currents of considerable velocity because of the draining away of water from the flat, or the return of water on to the flat. The rampart (see Stephenson, Tandy and Spender) behind which it lay acts as a barrier both to the entrance of the rising tide and to the outflow of the falling tide. When the rising tide reaches the level of a gap in the rampart, it flows in rapidly there, since elsewhere it is impeded by the greater height of the rampart. This results in a current along the moat which disturbs sediment and this was collected in the jar. In the same way, as the tide falls, water drains off the flat and is impeded in its outflow by the rampart, being able to escape only by the gaps. This again causes a current along the moat stirring up sediment.

The jar at A (Text-fig. 3 (*c*)) lay in a part of the moat much less subject to currents, and, as might be expected, the quantity of sediment collected was smaller. The peaks in



TEXT-FIG. 3.—The relation of the wind to the sediments collected at A, C, D and E. (*a*) Diagram of wind force and wind direction from 9th December to 2nd June. A cross on the diagram indicates N. wind during the day. (*b*) Average wind velocity per week. (*c*) Total amount of sediment in gm. and its grades at A. (*d*) Total amount of sediment in gm. and its grades at C. (*e*) Total amount of sediment of gm. and its grades at D. (*f*) Total amount of sediment in gm. and its grades at E. In cases where the jars were exposed for more or less than a week, the results have been calculated as for seven days.

the sediment curve again follow the peaks in the wind curve, with an apparent exception at the sediment peak from 31st March to 7th April. During that period there was, on several days, fresh north wind in the afternoons, and when we come to compare this curve with those for jars further north of the reef edge, we find that in general N. wind is much more important than S.E. wind in moving sediment. The largest quantity of sediment occurred during the week 24th February to 3rd March, when there was both S.E. wind and strong N. wind. If we compare the quantity of sediment collected during periods of strong S.E. wind with the quantity collected during that week, it seems likely that the N. wind is responsible for a large fraction of the sediment. Similarly, the peak from 30th December to 6th January is large, and again N. wind during that week may have been a partial cause.

The chief difference from position B lies in the considerably diminished effect of the S.E wind and the increased importance of the N. wind. The fact that the N. wind has an important effect so near the S.E. edge of the flat is surprising, and in this case, as with the other jars of the series, is to be accounted for by the fact that the island-reef (see Spender, 1930) is stable when exposed to the normal S.E. wind, but is unstable when exposed to N. wind. On the S.E. the reef is steep-to, while to the N. it shoals gradually. Thus during the normal S.E. wind the force of the waves is broken before they reach the sand-flat and there is little disturbance of sediment. The N. wind, on the other hand, attacks the sand-flat from its unprotected side and there is a greater disturbance of sediment.

At C (Text-fig. 3 (*d*)) further to the north, where the level of the flat is higher, the sediment was smaller in quantity than at either B or A. The curve is still closely related to the wind velocity with, as in the case of A, an apparent exception from 31st March to 7th April. The disagreement from 31st March to 7th April is in accord with the disagreement at A on that date and has the same explanation, *i. e.* N. wind. The highest peak on this curve is again during the period of strong N. wind, 24th February to 3rd March, and it is by far the most important peak, showing that the effect of N. wind far outweighs the effect of S.E. wind as one goes to the north of the reef. As at B, the average height of the curve during the calmer summer period is less than it is during the steady winds of winter.

The jar at D (Text-fig. 3 (*e*)) in the anchorage showed interesting differences from A, B, and C. The agreement with the wind curve is still shown, but the few disagreements are now much more marked. These are shown in the periods 6th to 13th January and 31st March to 7th April. The first week was one in which there was north wind in the afternoons and the second coincides once more with the effect of N. wind shown also at B, A and C. The effect of S. wind on the sediment is now very small indeed, but the effect of any N. wind is very large. The outstanding peak 24th February to 3rd March is the period of strong N. wind and, apart from that, there are only two important peaks, both being associated with N. wind.

Still further to the north, where the jar E (Text-fig. 3 (*f*)) was placed, north wind is the only wind of importance. The quantity of sediment was extremely small except during N. winds. The chief difference from D is shown by increased N. wind effect from 6th to 13th January, 24th February to 3rd March and 31st March to 7th April. In D and E the quantity of sediment is not increased when the steady S.E. trade winds begin.

It was not found possible to maintain jars in the deep water near the island regularly, because of liability to loss in rough weather or inability to take them in on a specified day from a small boat. Two positions, H and I, were, however, examined for four consecutive weeks (4th February to 3rd March). One of these (I) lay to the south-east of the Gap B, at a depth of 7·5 m. below mean sea level, and one (H) to the north of the shingle mound at a depth of about 11 m. below mean sea level (see Text-fig. 1 and Table II). The sediment in the jars was generally very fine in grade, though it was definitely coarser when the quantity of sediment was large. The relation to wind force was close, and as before, a N. wind produced more effect than a S.E wind. Both jars were exposed to S.E. wind, but the I jar was sheltered from the N. wind by the reef. In spite of this the N. wind had a considerable effect.

TABLE III. SERIES I.

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
I.1	Out 6.v.29 In 12.v.29	6	66·6	3·0	3·4	7·8	15·3	29·4	25·7	15·
I.1*a*	Out 5.v.29 In 12.v.29	7	27·2	5·2	4·6	7·1	9·4	17·5	21·3	35·1
I.2	Out 5.v.29 In 12.v.29	7	2·5	..	..	..	..	1·3	3·0	95·7
I.2*a*	Out 5.v.29 In 12.v.29	7	5·8	..	..	..	1·6	2·0	4·0	92·5
I.3	Out 5.v.29 In 12.v.29	7	83·0	0·9	0·8	1·5	2·6	10·0	58·1	24·7
I.3*a*	Out 5.v.29 In 12.v.29	7	24·3	..	0·3	0·2	0·5	2·6	18·5	77·9
I.4	Out 5.v.29 In 12.v.29	7	76·1	1·7	1·7	3·0	6·9	25·8	45·8	15·3
I.4*a*	Out 5.v.29 In 12.v.29	7	6·3	..	..	1·4	0·5	1·3	0·2	96·6
I.5	Out 5.v.29 In 12.v.29	7	17·3	3·9	3·1	4·1	7·0	21·8	27·9	32·2
I.5*a*	Out 5.v.29 In 12.v.29	7	11·5	..	..	..	1·5	1·8	2·0	94·8
I.6	Out 5.v.29 In 12.v.29	7	120·6	5·8	5·4	8·7	16·9	42·6	15·7	5·0
I.6*a*	Out 5.v.29 In 12.v.29	7	11·7	..	1·1	2·0	4·2	15·4	23·3	54·0

Another jar was placed in a position (F) in the mangrove swamp (see Text-fig. 1 and Table II) for about three months and the sediment collected weekly. It was put in a small pool surrounded by mangroves towards the S.E. end of the swamp. Usually only a small quantity was obtained and a high proportion of this was of mangrove origin. The quantity collected was too small for any relation to weather conditions to be made out. There was very little calcareous material, and organic matter and ash (p. 115) were invariably high. For one week a series was placed at different positions in the mangroves (see Text-fig. 1). One of these (III_1) was among the roots where the trees were close together, one (III_2) was in a sandy pool, one (III_3) was on a mud flat, and one in the usual F position. There was only a little over a gramme of sediment collected in any jar and there was no relationship shown to locality. In all cases the sediment seemed to be of mangrove origin.

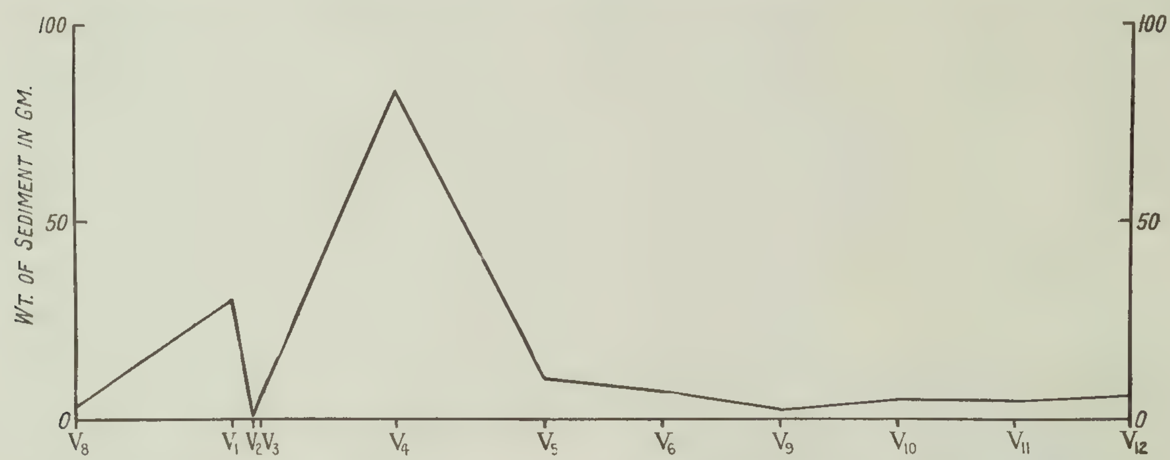
It was only possible to examine the sedimentation at five positions regularly, but to settle various doubts which arose, several series of jars were placed on or near the reef flat during the winter—the period of steady S.E. wind. The quantity of sediment in the moat, for example, was unexpectedly high, and it was difficult to be certain of the origin of this sediment. To study the conditions in the moat, a series of jars was placed along it, both in sheltered positions behind the rampart and in exposed positions at the gaps. In

TABLE IV. SERIES V.

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½-3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
V.1	Out 16.vi.29 In 27.vi.29	11	29·9	..	..	..	..	..	..	..
V.2	Out 16.vi.29 In 27.vi.29	11	0·1	..	..	..	..	..	..	100
V.3	Out 16.vi.29 In 27.vi.29	11	5·0	2·5	1·7	2·3	6·4	17·5	23·3	46·4
V.4	Out 16.vi.29 In 27.vi.29	11	82·7	..	..	..	..	..	..	..
V.5	Out 16.vi.29 In 27.vi.29	11	10·3	3·3	0·1	0·2	0·3	0·7	1·7	93·7
V.6	Out 16.vi.29 In 27.vi.29	11	6·8	..	..	..	10·9	16·8	17·7	54·6
V.8	Out 16.vi.29 In 27.vi.29	11	3·0	..	..	..	..	0·7	1·1	98·1
V.9	Out 16.vi.29 In 27.vi.29	11	2·2	..	..	..	0·5	9·0	15·5	75·0
V.10	Out 16.vi.29 In 27.vi.29	11	5·0	..	..	..	..	..	0·8	99·2
V.11	Out 16.vi.29 In 27.vi.29	11	4·5	..	..	..	..	..	0·7	99·3
V.12	Out 16.vi.29 In 27.vi.29	11	5·6	..	..	..	..	..	0·4	99·6

addition a parallel series of jars was placed on the flat, each of these being opposite a jar in the moat. The position of these jars is shown in Text-fig. 1 (I_1–I_{6a}). The jars on the flat lay at a considerably higher level than those in the moat, and so would only collect sediment when the tide was more than half-full. Those in the moat, on the other hand, were either covered all the time, or only uncovered for a short time at the lowest tide. The jars in the moat collected much more sediment than those on the flat (Table III) with the exception of the jar in the western end of the Fungia Moat, which collected less than its corresponding jar on the flat. The quantity collected in Gap B was of the same order of magnitude as in the moat jar B. Gaps did not always show a higher result than sheltered positions, and an examination of the sediment in the jars showed that the direction from which it had come, as indicated by the direction it was piled up in the jar, was not constant. This tilt did not indicate that it had come over the rampart. The largest quantity of sediment was obtained in the jar I_6, which is well sheltered and far from a gap. The reason for this exceptionally high result is difficult to understand. The lowest result (obtained in the jar in the Fungia Moat) is equally unexpected, but in this case it is notable that in the western end, where the jar I_2 was placed, the bottom is sandy only in patches and is covered in most places with coarse shingle. Here only fine silt (less than $\frac{1}{2}$ mm. diameter) collected, while in the other moat jars sand varying from very coarse to very fine was obtained. On the flat to the north of the moat the sediment was much finer in grade than in the moat.

A second series of jars was put out in a N.N.W.-S.S.E line. The positions of these are shown in Text-fig. 1 (V_{1-12}). This series extended from deep water well to the south-east of the reef across the flat to the deep water north of the reef. In the deep water to the south-east (12 m. below mean sea-level) only mud collected (Text-fig. 4 and Table IV). In the breaker zone there was a moderate quantity of sand of medium grade, on the rampart (15 cm. above mean sea-level) there was only a very small quantity of very fine material, and in the shallow moat beyond a small quantity of sand of mixed grade. The



TEXT-FIG 4.—Sediments of series V. in a S.S.E.—N.N.W. direction across the flat. The horizontal scale is only approximate.

fact that the jar on the rampart collected only a very small quantity of material, suggests that the sand in the moat jars is collected during a to-and-fro movement of the sand in the moats themselves with the rise and fall of the tide. Had it been caused by sand coming over the rampart, the rampart jar would have contained more. The nature of the material collecting in the jar on the rampart was examined in two other positions, and both of these showed only a small quantity of very fine material. The direction of the piling in the moat jars and the fact that the largest quantity of sediment does not necessarily collect at the gaps supports this view. The jar on the flat to the north of the moat contained an unexpectedly large quantity of sand of mixed grades. The flat here is composed largely of cemented coral conglomerate with at most a light covering of sand, which often shows lines of streaming. The jars lying further to the N.W. had only comparatively small quantities of material generally of fine grade, especially in the deeper jars in the anchorage (V_{11} and V_{12} at 5·8 and 12 m. below mean sea-level respectively). This series showed definitely that during the normal S.E. weather only a very small quantity of material comes across the flat from the breaker zone, and that the material collected, more especially in the moat, is the result of local movement of an oscillatory nature.

The movement of sand across the flat was tested by a series of jars put out in an east-west direction across the reef (see Text-fig. 1 (II_1–II_6) and Table V). These jars were partly buried, their tops being only 8 cm. above sand-level, so that they collected relatively more than the A jar which was at the western end of the series. None of the jars contained a large quantity of sediment, and there was a gradual decrease as the mangrove swamp was approached. The highest result was obtained to the west, on the sand flat.

While the foregoing account gives some conception of the movement of sediment on a coral reef, there are certain qualifications which should be made. In the first place Low Isles reef, while typical of a large number of island-reefs lying inside the Barrier, is by no means typical of coral reefs in general (Steers, 1929). Secondly, the sediment collected in jars is liable to error from various sources. The height of the jars above the reef flat makes a considerable difference in the quantity of sediment collected. On one occasion

TABLE V. SERIES II.

Position.	Date.	Number of days out.	Amount of sediment in grammes.	Percentage of each grade of sediment.						
				> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
II.1	Out 12.v.29 In 19.v.29	7	21·4	2·4	1·1	1·9	3·6	11·0	30·9	49·1
II.2	Out 12.v.29 In 19.v.29	7	16·2	4·6	2·4	4·5	5·9	12·2	18·5	52·0
II.3,4	Out 12.v.29 In 19.v.29	7	(32·2)	5·5	1·0	1·2	2·6	7·4	18·4	63·9
II.5	Out 12.v.29 In 19.v.29	7	3·0	5·5	1·1	0·7	2·2	6·2	7·0	77·3
II.6	Out 12.v.29 In 19.v.29	7	3·6	8·8	0·3	0·9	1·2	5·8	11·2	71·8

a jar was put beside each of the jars A, B and C, but with the mouth about 15 cm. lower. The quantity of sediment in the jars at a lower level was from three to five times more than in the normal jars. In addition jars placed close together did not always collect the same amount of sediment. Organisms such as hermit crabs and small fish, which are of fairly frequent occurrence in some of the jars, stir up the collected sediment and material may be lost. Finally, the effect of waves and currents not only adds sediment to the jars but may also have a certain action in removing sediment. One jar (G, Text-fig. 1) was left out close to the C jar at the oyster pen for eighteen weeks, and although frequently examined the sediment was not collected till the end of this period. The quantity of sediment present then was only a third of the total quantity collected in the C jar during the same period. While a certain amount of this loss can be ascribed to the activities of fish and hermit crabs, it is likely that currents were also responsible. Since the material collected in that position was always of fine grade (about 95% was less than ½ mm. diameter), it would be readily stirred up and lost. A jar placed close to the B jar in the moat was almost filled in three weeks, and it is unlikely that much loss would have taken place as the sediment was of very coarse grade.

The actual amount of permanent deposition was measured only in one place—in a sandy pool in the Western Moat. A clean cement block, the level of which was a few centimteres above that of the sand, was left exposed from 6th November till 17th June. It was by then coated with a layer of fine sand and silt, the former being held in place to some extent by a growth of filamentous algae. The sediment from 81 sq. cm. was collected. It weighed when dry 17·9 gm. It is, however, unsafe to generalize from this result, for the surface, offering as it does a firm foundation for algal growth, enables sediment to be entangled and held in place.

Changes in the spits and ridges of the reef flat were observed during winds of unusual force or direction. A north wind, for example, in addition to causing an exceptional movement of sediment below the sea surface, also caused considerable changes in the outline of the sand cay itself— a phenomenon which has been observed elsewhere (Davis, 1923). These disappear when the normal S.E trade wind returns. To measure the results of sedimentation over prolonged periods, it would be necessary to compare accurate surveys of the reef made at different dates.

Grades of the Sediments.

All the samples from the five jars A–E with the exception of that from 5th to 12th May were graded. Sieves with circular mesh varying from $\frac{1}{2}$ mm. to 3 mm. were used and the fractions determined by weighing. The results are shown in Text-figs. 2 (*b*) and (*c*), and 3 (*c*), (*d*), (*e*) and (*f*), and Table II. From these the general result is obtained that, when winds are light, the percentage of fine material is high, while with a strong wind the percentage of the finest material is small and that of the coarser material increases. It would have been desirable to make mechanical analyses of all the finer grades, as has already been done for coral sands by Vaughan and others (1918), Bramlette (1926) and Goldman (1926). A few samples from Low Isles reef are being dealt with in this way. The results will appear in a later report.

In B, Text-fig. 2 (*c*), the peaks in the curve are followed closely by the peaks in the coarser grades, and the diagram Text-fig. 2 (*b*) shows how, during the summer unstable period, the percentages of the different grades are irregular, while, during the winter period of steady S.E. wind, the percentages of the different grades are fairly constant. Only at B are the coarser grades of importance, while in all the others, material less than $\frac{1}{2}$ mm. diameter forms a very high percentage of the total and an insignificant quantity of the very coarse material is present. At C, from 24th February to 3rd March, the rise in the coarser grades is illusory, being caused by a gastropod and a crab, neither of which should, of course, be recorded as sediment. At D and E, even when the N. wind caused a big peak, there was no appreciable change in the grade of the sediment. This may have been partly due to the greater depth of these jars, and also because the E jar was considerably above the bottom. The D jar, however, was no further off the bottom than those on the flat.

Origin of the Sediments.

The sediments consist of a mixture of sand with a varying quantity of fine detritus. When the sand is examined microscopically, about half the fragments can be easily identified. Of these, about one third are coral, one third foraminiferan (mainly of the *Orbitolites* and *Tinoporus* types), and one third a mixture of alcyonarian spicules and bits of calcareous algae, crustaceans, gastropods, echinoderms and so on, of which the second forms more than half. The proportion of calcareous algae is, however, sometimes higher than this. Of the unidentifiable portion, coral probably forms a high proportion.

The fine detritus consists mostly of unrecognizable material with a few recognizable fragments such as dead diatoms, cyanophycean threads and bits of *Thalassia* with tintinnoid tests and the remains of small crustaceans and lamellibranch larvae. There were always present, too, a few living flagellates, ciliates and diatoms (*Navicula, Nitzschia* and *Bacillaria* being the commonest forms) and occasionally small worms and crustaceans.

Spawn of various kinds was deposited on the inside or outside of the jars and coral planulae settled occasionally from January to April. The latter were found on the A, B, E, H and I jars, that is, on all the jars which stood among living coral but not on any of the others.

Besides these, larger animals sometimes got into the jars and stayed there. On one occasion (2nd to 9th February) there were 60 *Cavolinia* in the H jar. Small gastropods which fed on the algae growing on the glass sides were frequent in all the jars and small fish or hermit crabs were occasionally found too. This was often the case in the C and D jars, particularly the latter. On one occasion eight large hermit crabs had all collected in the D jar at one time. The movement of such large creatures as these would naturally stir up any fine sediment which had collected in the jar and might result in considerable loss. During April and May masses of unattached filamentous algae were floating about in the anchorage, and were found in the D and E and to a less extent in the C jars.

Much more careful studies of reef sands from Murray Island and the Bahamas by Wayland Vaughan and others (1918), Goldman (1926) and Bramlette (1926) give results agreeing fairly well with this, although coral in their samples is probably a little less important.

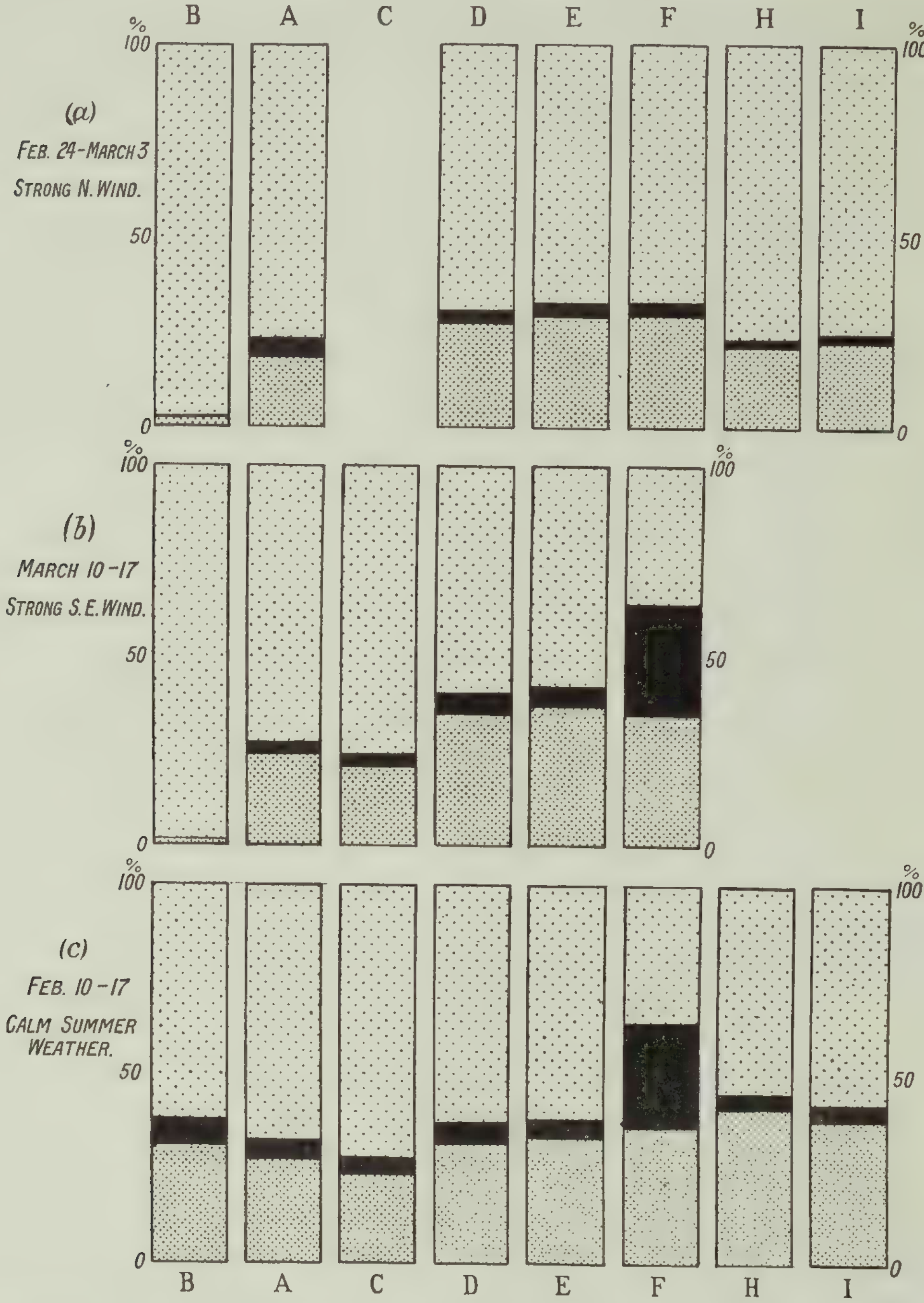
Chemical Composition of the Sediments.

Several series of samples were analysed to find the percentage composition of the different grades in the different jars and the relation of this to their position on the flat. It was considered sufficient to determine (*a*) the percentage soluble in 1/3 HCl boiling for three minutes, (*b*) the ash, (*c*) the organic matter. Three series of samples were examined in this way.

A weighed quantity of the sediment was treated with 1/3 HCl and finally boiled for three minutes. The insoluble residue was collected, washed, dried at 100° C. and weighed. It was then ignited to constant weight. The loss of weight on ignition was largely owing to organic matter and is described as such.

The first series was that collected during a period of strong S.E. wind, 10th to 17th March. Taking each sample as a whole (Text-fig. 5 (*b*) and Table VI), the quantity of material soluble in acid decreases from B (98%) to A (73%). C (76%) is almost the same as A, while D and E are slightly lower (60% and 58%). The ash percentage is complementary to the acid-soluble fraction. Organic material amounts to no more than 6% and is least at B. Only B and A were examined grade by grade, and in these two cases it was found that almost the whole of the insoluble material was present in the finest grade (less than ½ mm. diameter) while organic material was higher than in the coarser grades (Table IX).

The samples collected during the period of strong N. wind (24th February to 3rd March) were also examined. The results of the analyses of the complete samples is shown in Text-fig. 5 (*a*) and Table VII. B and A are almost the same as during the strong S.E wind, but D and E show an appreciably higher percentage of soluble material. The contents of C were not available for analysis. All four samples were analysed grade by grade, and as before, it was found that in all cases most of the insoluble material is present in the finest



Text-fig. 5.—Chemical composition of the sediments in different kinds of weather.

(*a*) Strong N. wind. — Soluble in $\frac{1}{3}$ HCl.
(*b*) Strong S.E. wind. — Loss on ignition (minus CO_2).
(*c*) Calm summer weather. — Ash.

grade and this is due only in part to organic material. A certain amount of plant material was present in the coarsest grades and this accounts for the decrease in soluble material there (Table IX).

TABLE VI.

Series 14. Strong S.E. wind. 10–17/3/29.

	Sol. in 1/3 HCl. %	Ash. %	Loss on ignition. %
A.	72·6	24·2	3·2
B.	98·1	1·6	0·3
C.	75·8	21·0	3·2
D.	59·7	34·7	5·6
E.	57·9	36·9	5·2
F.	36·1	34·8	29·0

TABLE VII.

Series 12. Strong N. wind. 24/2/29–3/3/29.

	Sol. in 1/3 HCl. %	Ash. %	Loss on ignition. %
A.	76·9	18·1	5·0
B.	97·1	2·4	0·5
D.	69·2	27·2	3·6
E.	67·3	28·9	3·8
F.	35·3	32·0	32·7
H.	76·8	20.9	2·3
I.	75·2	22·2	2·6

TABLE VIII.

Series 10. Summer calm weather. 10–17/2/29.

	Sol. in 1/3 HCl. %	Ash. %	Loss on ignition. %
A.	67·4	27·2	5·4
B.	61·9	30·8	7·3
C.	72·1	23·3	4·6
D.	62·7	31·7	5·6
E.	61·8	33·1	5·1
F.	36·2	35·9	27·9
H.	54·9	40·9	4·2
I.	57·8	37·6	4·7

The last series examined was collected during calm summer weather (10th to 17th February) and as the samples were small they were not graded for analysis. The results are shown in Text-fig. 5 (*c*) and Table VIII. The composition of the sediment in A, C, D and E shows little change, but in B, probably because of the large proportion of fine material present, the insoluble fraction is as high as in A. There is also a slight increase in organic material. In F the percentage of organic material and also of ash was always high though irregular. H and I resembled E most closely.

The chemical examination of the sediments shows that coarse material is almost all soluble, while material finer than ½ mm. diameter contains a certain percentage of insoluble material. The changes from S.E. to N.W. across the flat are not caused by a change in the nature of the sediment, but only by a difference in size composition.

TABLE IX.—*Percentage Composition of the Different Grades of Sediment.*

	Position.	Date.	> 3 mm.	2½–3 mm.	2–2½ mm.	1½–2 mm.	1–1½ mm.	½–1 mm.	< ½ mm.
Soluble in 1/3 HCl	A	March	←			92·3		→	69·9
Loss on ignition		10–17				1·7			3·4
Ash						6·1			26·7
Soluble in 1/3 HCl	B	March	98·7	98·9	98·8	98·8	98·8	98·8	90·1
Loss on ignition		10–17	0·4	0·3	0·3	0·3	0·3	0·2	1·2
Ash			0·9	0·8	0·9	0·9	0·9	1·0	8·7
Soluble in 1/3 HCl	A	Feb. 24	←	92·9	→	98·1	99·6	96·3	71·3
Loss on ignition		Mar. 3		4·7		. .	. .	0·8	6·1
Ash				2·5		1·9	0·4	3·0	22·6
Soluble in 1/3 HCl	B	Feb. 24	98·6	98·6	98·6	98·7	98·7	98·6	87·4
Loss on ignition		Mar. 3	0·6	0·5	0·4	0·4	0·4	0·3	1·4
Ash			0·9	1·0	1·0	0·9	1·0	1·1	11·3
Soluble in 1/3 HCl	D	Feb. 24	←			81·7	→	86·3	69·1
Loss on ignition		Mar. 3				9·3		3·7	3·5
Ash						9·0		10·0	27·4
Soluble in 1/3 HCl	E	Feb. 24	←			87·5		→	67·0
Loss on ignition		Mar. 3				6·1			3·7
Ash						6·5			29·3

CHEMICAL CHANGES IN THE SEDIMENTS.

It was frequently found that the lowest part of the sediment collected in the jars was black in colour, there being generally a definite line of separation between the blackened and the unblackened sediment (see Plate II, 7). Blackening was most likely to occur either where sediment was deep or when it was fine in grade. If allowed to stand for some days, the black layer extended upwards to quite near the surface of the sediment. It was suspected that this change was caused by deoxygenation of the lower layers. Probably bacterial decomposition of the small quantity of organic material present in the sediments led to sulphide formation (*cf.* Ellis, 1925). An examination of the sand on the reef flat itself showed that black sand was generally found at a depth of an inch or two. The depth to the blackening was variable on the flat. Where movement was taking place, *e. g.* in the moat or where there were present ridges or sand spits caused by the meeting of opposing currents, the depth to the black layer was great—as much as a foot or more. The black layer was found over the whole of the reef flat and even in the anchorage. The distribution of the blackening showed no relationship to the mangrove swamp and is apparently unaffected by its proximity. The oxygen content of this black sand was tested and was found to be very low, while there was a copious liberation of hydrogen sulphide on addition of acid. Sulphides were measured quantitatively and found to be present in small quantity in the surface sand, increasing gradually with depth to at least 15 cm., the greatest depth tested. On exposing the black layer to fully oxygenated water the colour changed gradually to grey, and in a few days was indistinguishable from the usual colour of the surface sand (*cf.* Bruce, 1928).

To test the rate of blackening and its cause, samples of surface sand from different parts of the reef flat were put into glass tubes about a foot and a half long, closed at one end. The samples were wetted and covered with sea-water and the course of blackening observed. Mud from the sea bottom in the vicinity of the reef was also tested. As controls, sand samples which had been well washed with sea-water to remove finely divided organic matter and from which all larger pieces of organic matter had been removed by hand were placed alongside. In a few days the surface samples had blackened completely while the washed controls showed only a slight darkening. The muds from the sea bottom showed blackening only in patches, probably where there was a larger piece of organic matter. Sands of fine grade blackened more quickly than those of coarse grade, and those taken from positions where there was considerable sand movement darkened almost as slowly as the washed controls. Blackening is caused by the decomposition of the organic material, which is chiefly present in the finest grades. Blackening of the sand was found occasionally on other types of reefs, but it was nowhere found so commonly as on Low Isles reef. The probable explanation of this lies in the higher level of Low Isles reef and the protection from wave action given by the rampart.

PART II. BORES ON LOW ISLES REEF.

The distribution of the surface sediments on Low Isles has been described by Stephenson, Tandy and Spender elsewhere in these reports. There are considerable differences, the sediments varying from coarse sand to rock on the flat and mud in the mangrove swamp. The question of the composition of the deeper layers of coral islands is a much disputed one, and the most recent work on the Barrier Reef (Richards, 1928) has shown that there is not necessarily coral rock lying as a foundation to the reef system. In the bore on Michaelmas Cay, it was found that coralline sand extended to at least 400 ft. No bores have been made on the other reefs of the Barrier Reef system, but some curious observations have been made by the lighthouse authorities in attempting to drive in piles as a foundation for lighthouses. It was found difficult to drive the piles through the sand for the first few feet, but thereafter the difficulty lay in preventing them from sinking and disappearing of their own accord.* This suggested that the structure of these islands was different from that of Michaelmas Cay. In view of the results obtained on Low Isles, it seems probable that the structure found there is characteristic of quite a number of coral reefs in the Barrier Reef region.

The bores made on Low Isles were shallow bores, the maximum depth reached being 17 feet. The apparatus used was lent by Prof. Sir T. W. Edgeworth David, F.R.S. It was simple in construction, consisting of a casing and a piping with a pump or other tool at its lower end. The bores were made by hand. The samples are not very reliable quantitatively for cores are not obtained, and the loose material tends to work past the tool from

* Information in a personal communication from Prof. H. C. Richards.

above. In addition, as the tool has to be removed to collect each sample, soft material tends to ooze up the tube. For this reason, the results described below have to be interpreted with a certain amount of caution, though from a general point of view they are reliable.

Description of the Bores.

Altogether five bores were made, but of these only four reached 12 ft. or deeper. The position of the bores is shown in Text-fig. 1. The first bore was made on the sand flat about 150 yards from the sand cay, the second was made on the cemented platform near the S.E. beacon, and the third was made on a mud flat in the mangrove swamp. A bore was also made on the sand cay itself and a very shallow one in the moat.

Bore on Sand Flat.

3′ above Admiralty datum.

0′–3′. Coarse sand and coral shingle with sand predominant. The sand below the surface was black while the shingle particles on being broken up were white.

3′–6′. From 3′ to 5′ the sand with shingle fragments continued, but at 5′ there was an abrupt change to a soft, light-grey mud. The sand was black as far as it went. The pump and casing descended very readily into the mud when compared with the difficulty in penetrating the sand.

6′–9′. Fine mud as from 5′–6′. Penetration was very easy. There were only a few sand grains, which might have slipped past the pump inside the casing.

9′–12′. Mud of similar colour and consistency, still readily penetrated.

12′–15′. Mud similar in appearance and texture to that obtained from the other depths.

Bore on Cemented Platform.

3′ 6″ above Admiralty datum.

The surface is a platform of solid rock formed by the cementing together of dead coral fragments. It is hard, and has to be broken with a chisel. The platform is almost flat, but there are numerous depressions of an inch or two in depth which are partially filled with coarse sand. For ease in working, the bore was started in one of these depressions.

0″–6″. Sand and chips of platform material. The sand was black in the deeper parts.

6″–1′ 6″. Cemented coral fragments for the most part.

1′ 6″–3′. Coarse sand mixed with soft grey mud similar to that obtained in the deeper samples of the bore on the sand flat.

3′–5′ 4″. Sand and light grey mud.

At 5′ 4″ rock was met and, although this was not penetrated for more than a fraction of an inch, it was decided to abandon this bore and find whether this was an accidental occurrence, or whether a rock platform would be met everywhere at about this depth. A trial was made a few feet away from the first bore, using the chisel only, and no samples were taken. After the cemented rock had been passed at about 1′ 6″ the chisel went down readily to a depth of 15′. This seemed far enough to justify a third bore being made a few feet away. The first 3′ of the third bore were similar to the first 3′ of the first bore and so no samples were kept.

3′–6′. Sandy mud. The bore tube and casing entered readily. The sand may have been in part material from above slipping past the pump in the casing.

6′–9′. Soft grey mud with a little sand.

9′–12′. Soft grey mud with very little sand.

12′–17′. Soft grey mud. This sample may have been contaminated to some extent by seepage up the casing.

Bore on Mud Flat in Mangrove Swamp.

The surface is a soft black mud formed of detritus largely of mangrove origin. Just below the surface, at a depth of a few inches, the mud was redder in colour. The mud is of uneven firmness and it is common to sink into it to a depth of over a foot.

0′–1′ 6″. With care a core was taken to this depth with the casing, and it consisted very largely of mangrove detritus with a few shingle fragments and sand grains.

1′ 6″–2′. Fibrous mangrove material with shingle fragments and coarse sand.

2′–3′. Coarse sand and mangrove material.

3′–4′. Coarse sand and shingle.

4′–6′. Sandy mud with shingle fragments. The mud was light grey in colour and very like that brought up in the bores already described. There seemed, however, to be more sand and shingle fragments than was customary. Contamination from above would not be likely to account for the sand found in the deeper parts of this bore.

6′–9′. Soft grey mud with a fair amount of coarse sand and a few shingle fragments.

9′–12′. Mud and sand with shingle fragments. A certain amount of seepage up the tube seemed to have taken place.

12′–12′ 6″. Similar material to the previous sample.

Bore on Sand Cay.

At 14′ 6″ above Admiralty datum.

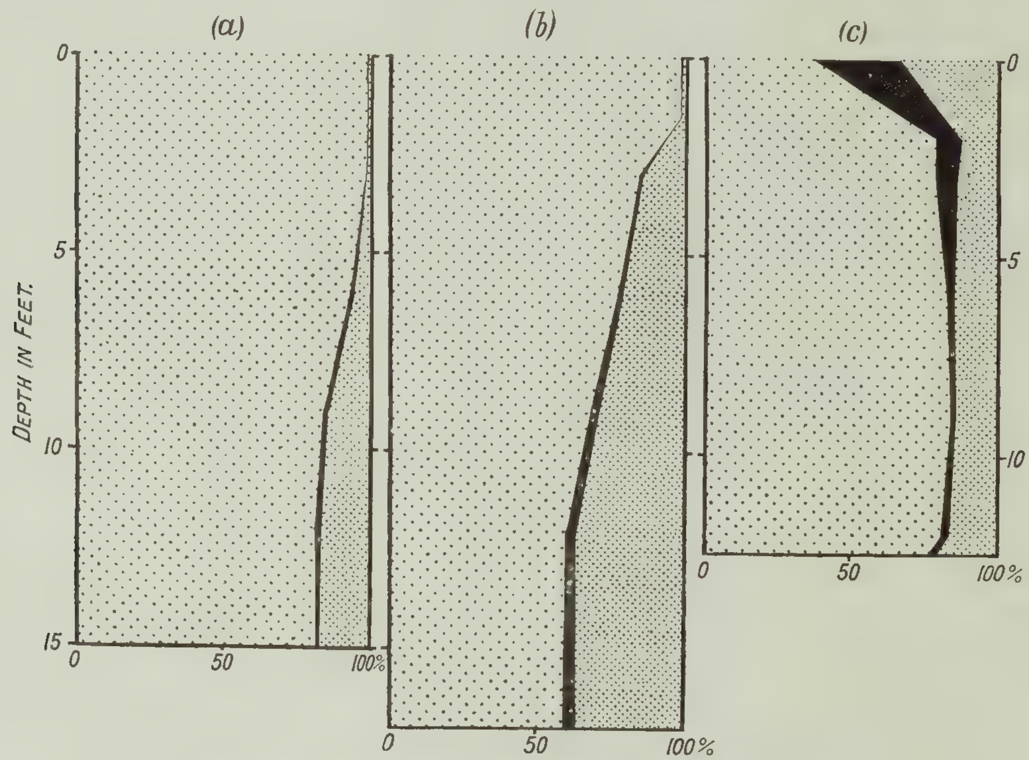
A bore was made about the middle of the sand cay to a depth of 14′ 6″. Only sand was found at all depths and there was no apparent change in the grade throughout. The depth, when we allow for the height above datum, is 2′ less than the depth to which sand was found in the bore on the sand flat 150 yards from the cay. From this result, then, no conclusions can be drawn as to the extension of the mud layer under the cay.

All the bores, with the exception of that on the sand cay, which is inconclusive because of the small depth which was penetrated in relation to Admiralty datum, demonstrate the presence at a varying depth of a layer of soft mud of considerable thickness beneath the flat. The fact that these bores are widely separated in position from one another, points to the probable universality of this layer beneath the reef flat of Low Isles. In the case of the cay and the N.E. shingle mound, it seems likely from the results obtained on Michaelmas Cay (Richards, 1928) that there is at least a much greater depth of sand at these positions than elsewhere. On the flat itself, where we find sand, the sand layer is deeper than where the surface is rock. Confirmation of this was obtained by making a shallow bore in the moat, the surface sand in which lies over a foot lower than the surface at the cemented platform near by. Mud was not found, although a bore was made to a depth of 3′.

It was unfortunate that a shortage of casing and piping did not permit of deeper bores being made in an effort to reach some stratum lying below the mud, but, as will be seen below from the chemical analyses, certain conclusions can be drawn tentatively regarding the composition of the reef under the flat.

Chemical Composition of the Material from the Bores.

Analyses of the material from all the bores except that on the cay were made in the same way as with the sediments which were collected on the surface of the flat. The results are shown in Text-fig. 6 and Tables X, XI and XII. It is apparent in each case that, as soon as the mud is entered, there is a rapid change in the chemical composition of the material, namely a decrease in the acid-soluble material and an increase in the percentage of ash. The percentage of acid-soluble material tends to decrease with increasing depth in the mud. Whether the decrease in the rate of change in the deeper part is real, or whether it is because of seepage up the bore tube, it is impossible to say.



Text-fig. 6.—Chemical composition of the bore samples.

(*a*) Bore on the sand flat.
(*b*) Bore on the cemented platform
(*c*) Bore in the mangrove swamp.

Soluble in $\frac{1}{3}$ HCl.
Loss on ignition (minus CO_2).
Ash.

A comparison of the composition of the mud on the sea bottom in the vicinity of Low Isles with that from the deeper parts of the bores is instructive. A series of samples was taken by dredge in a line from the mainland to the outer reefs. One was taken 3 miles W. of Low Isles, one $\frac{1}{2}$ mile N. and the other two 3 and 6 miles E. of Low Isles respectively. The results of the analyses of these samples are shown in Text-fig. 7 and Table XIII. With the exception of the sample from $\frac{1}{2}$ mile N. of Low Isles, there is a gradual rise in acid-soluble material and a decrease in ash and organic material as the outer reefs are approached. The composition of the remaining sample (taken $\frac{1}{2}$ mile N. of Low Isles) from the lee of the reef is affected by this proximity and is almost the same as the sample furthest out. These muds resemble in colour and texture those found in the deepest parts of the bores,

Table X.—*Bore on Sand Flat 150 yards from the Cay.*

Depth.	Nature of material.	Soluble in 1/3 HCl. %	Ash. %	Loss on ignition. %
Surface	Coarse sand	98·1	1·6	0·3
0′–3′	,, (black)	98·8	1·0	0·2
3′–6′	,, and fine mud	93·0	6·4	0·6
6′–9′	Grey mud	83·8	14·8	1·4
9′–12′	,,	81·2	17·0	1·8
12′–15′	,,	81·8	16·7	1·4

Table XI.—*Bore on Cemented Platform near S.E. Beacon.*

Depth.	Nature of material.	Soluble in 1/3 HCl. %	Ash. %	Loss on ignition. %
Surface	Cemented coral fragments	97·5	2·0	0·6
0–1′ 6″	Coarse sand (grey)	98·2	1·6	0·2
1′ 6″–3′	Sandy mud	83·9	14·8	1·4
3′–6′	,,	76·6	21·3	2·1
6′–9′	Soft grey mud	67·9	29·3	2·8
9′–12′	,, ,,	59·5	37·2	3·3
12′–17′	,, ,,	59·2	37·3	3·5

Table XII.—*Bore on Mud Flat in Mangrove Swamp.*

Depth.	Nature of material.	Soluble in 1/3 HCl. %	Ash. %	Loss on ignition. %
Surface	Black mangrove mud	35·8	33·9	30·3
0′–2′	Mangrove mud	77·8	12·8	9·3
2′–3′	,, with sand and shingle	78·0	14·9	7·2
3′–6′	Sand, shingle and grey mud	82·6	15·3	2·0
6′–9′	Mud with a little coarse sand	83·6	14·7	1·7
9′–12′	Sandy mud	80·7	17·2	2·1
12′–12′ 6″	Chiefly mud	75·9	21·4	2·7

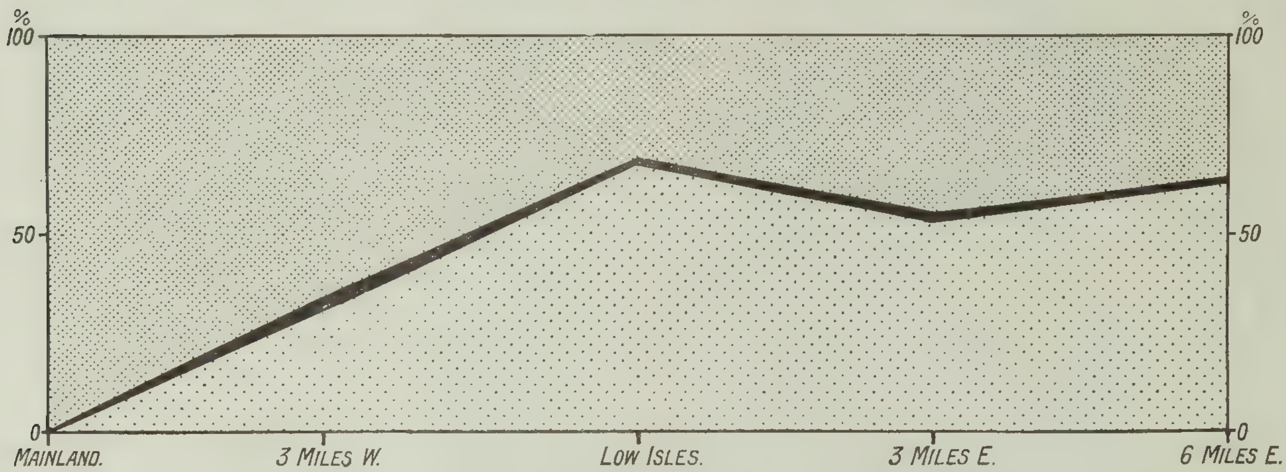
Table XIII.—*Sea Bottom Samples.*

Position with reference to Low Isles.	Soluble in 1/3 HCl. %	Ash. %	Loss on ignition. %
3 miles W.	32·4	63·9	3·7
½ mile N.	67·4	31·0	1·6
3 miles E.	53·0	44·8	2·2
6 ,,	62·5	35·8	1·7

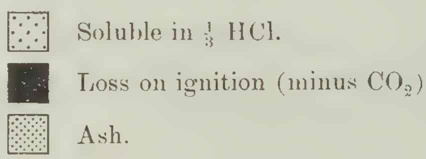
the chief difference lying in the greater percentage of acid-insoluble material on the sea bottom. Even so, the percentage of insoluble material from different depths under the flat is much greater than would be anticipated from the level at which it is found, and, in the deepest layers, exceeds that of the sea bottom sample taken ½ mile N. of Low Isles.

Attempts to understand the origin and structure of Low Isles are beset by difficulties, some of which can only be removed by making several deeper bores. The general presence of a cap of sand or rock overlying a considerable depth of soft mud is, to say the least, unexpected, and the whole reef would seem to be rather unstable. The nature of the supporting structure of Low Isles has still to be discovered.

It would be expected that the origin of the mud was the fine material which is carried on to the surface of the flat. It has been shown on p. 113 that a fairly high percentage of this fine material is acid-insoluble and that the coarser material is acid-soluble. This



TEXT-FIG. 7. -Chemical composition of sea-bottom samples in a section from the mainland to the outer reefs. For the purpose of the diagram, the mainland is represented as consisting entirely of insoluble material.



fine material, by working its way between the coarser particles, might add to the mud below the sand cap. There are, however, several serious objections to this explanation of the origin of the mud layer. In the first place, the percentage of insoluble material in the finest grades on the flat is not generally high enough to account for the insoluble material under the flat. Secondly, if this were the cause, it offers no explanation of the increase in insoluble material with depth below the flat nor of the very abrupt transition which occurs under the flat from sand to mud. The occurrence of this material under the solid rock of the cemented platform and under the mangrove swamp is also difficult to understand.

It has already been mentioned (p. 116) that black sand is found under the surface over the whole of the reef. This is almost denuded of oxygen, contains sulphides and has a low pH value. The mud which occurs underneath, however, is light in colour and has a high pH value (the same as that of the sea). If a sample of the mud is allowed to stand for some time it gradually becomes black except on the surface, where it is exposed to aërated water. It seems to be beyond doubt that this blackening is associated with the removal of oxygen and the formation of sulphides by micro-organisms in the mud. If this is so, it is very difficult to understand why the mud *in situ* is not black. It is, in any case, still less probable that the mud under the flat originated from above, where all the fine material is black. If, on the other hand, the mud under the flat is the same as that on the sea bottom, it is difficult to understand how this material finds its way so close to the reef flat surface under the sand cap.

Mechanical and mineralogical analyses of the bore samples are being made and these will be described later.

Thanks are due to Mr. A. G. Nicholls, Mr. M. A. Spender and Mr. J. Colman for help in making the bores. For the results of the bore on the sand cay we have to thank Mr. E. C. Marchant and Mr. M. A. Spender.

PART III.—THE EFFECT OF SEDIMENT ON CORALS.

From the early days of the study of coral reefs, it has been recognized that coral seas are generally very clear and free from sediment. This has led to the belief that clear water is essential for coral growth, and more recently Wood-Jones (1912) has put forward a theory of coral-reef formation in which sedimentation plays a large part by restricting the regions in which coral can grow. This author has made some extremely interesting observations on the subject but experimental work is lacking. Various authors have noted the time required to kill a coral after burial, and Wood-Jones has observed the removal of small quantities of sediment by *Fungia*. The lagoon inside the Barrier Reef of Australia, however, is by no means clear. The water is generally less clear than the English Channel, the average reading of the Secchi disc being about 8 metres as against about 12 there (Poole and Atkins, 1928; Russell, 1928). The minimum recorded in the Barrier Reef lagoon during the year was $4\frac{1}{2}$ m. and the maximum slightly over 20 m. Beyond the Barrier the water is generally very clear and the Secchi disc reading may be as high as 40 m. In spite of this turbidity inside the Barrier, however, coral grows abundantly. In addition, as is shown in Part I of this paper, the amount of sediment on Low Isles at places where coral is growing richly (*e. g.* in the moats) is very large, and may vary from fine silt to coarse sand. This is also discussed by Stephenson elsewhere in these reports. For this reason, it was decided to try the effect of varying kinds of sediment on living corals, not only on the reef itself but also in the laboratory.

Experiments on the Reef Flat.

Some experiments were made on the removal of sediment from corals living under natural conditions on the reef flat by covering them with sand and examining them at intervals. The sand was of mixed grade, and was taken from a position close to where the corals were living. Several localities in which the tidal movements and amount of sediment falling were known to be different were chosen for these experiments and several kinds of coral were marked in each locality. The results from the sediment jars (see Part I) show that more sediment falls in the B Gap than in the eastern end of the *Fungia* Moat, and more there than in the Western Moat. In spite of this fact, there was no important difference between the colonies in the different places. In all, eight types of coral were investigated, all of them belonging to genera common on the reef flat. Sand was put on two days running; the corals were then left uncovered for two days and this procedure continued for nine days in most cases.

Pocillopora bulbosa.—It is difficult for sediment, particularly if coarse in grain, to find a holding on the narrow branches of *Pocillopora*, and even when some has settled it is easily washed off again by any water movement. Large quantities of sand were put on top of one colony near the B position in the *Fungia* Moat (see Text-fig. 1) till there was sand lying on most of the branches, but after twenty-four hours this had always disappeared and the coral was perfectly clean. It is impossible to say whether this is caused by water movements or by the ciliary action of the coral itself.

Galaxea fascicularis.—In contrast to *Pocillopora* this coral is easily covered with sand, but nevertheless it cleaned itself very rapidly. It was almost buried under sand, but after twenty-four hours the polyps were invariably clean, and a little sand was found only on the solid platform from which the polyps project. This sand had been removed by the next day. The second colony investigated always cleaned itself completely each day. Since *Galaxea* shows plenty of holding space for sand, ciliary action probably plays a greater part here than it does with *Pocillopora*.

Favia.—Two types of *Favia* were chosen, one with small polyps and one with large. Eight colonies altogether were investigated—two in the *Fungia* Moat, four in the coral pen in the Western Moat, and two further west than the coral pen. On the whole, the large-polyped type cleaned itself more readily than the small-polyped type, but there was much individual variation. One small-polyped form was not completely clean after seven days, while another cleaned itself repeatedly in twenty-four hours. The large-polyped colonies were usually clean or almost clean after twenty-four hours. The effect of the wind is seen clearly in these experiments with *Favia*. Wind has a two-fold action: it increases water movement and so presumably helps in washing off sediment, but it also stirs up sediment from the reef flat which may be deposited on the corals. It is this latter action which is most clearly seen in our experiments. After the first two days there was a four days' calm, when the average wind velocity was not above six miles per hour. There followed three days (20th, 21st and 22nd June) of S.E. wind above fourteen miles per hour. When the wind velocity rises above ten miles per hour, the amount of sediment in the water shows a considerable increase. In several cases a coral which had been left clean on one of these days had some sand or fine sediment lying on it the following day. On the other hand, cleaning in some cases is apparently more rapid during the last three days of the experiment, *i. e.* when there is more wind.

Symphyllia recta.—This coral always cleaned itself completely in twenty-four hours.

Fungia.—Both the ordinary (*F. danai*) and the "daylight" (*F. actiniformis*, var. *crassitentaculata*) types of *Fungia** cleaned themselves completely in twenty-four hours on the two occasions on which they were tried.

Psammocora gonagra.—The sand is rapidly removed from the "leaves" of this coral, but it remains at the base of the colony in the angles of the "leaves" and is got rid of only very slowly. Untouched specimens growing on the reef flat often have their bases almost buried in sand.

Acropora.—Since the Acropores used were branching colonies, the same remarks

* Two types of *Fungia* were common on Low Isles reef. In one type the polyp was or might be fully expanded all day ("daylight" type); in the other it expanded fully only at night.

apply to them as to *Pocillopora*, and like it *Acropora* invariably cleaned itself in twenty-four hours even when it was left almost buried in sand. As before, it is impossible to say how much of this is caused by water movements and how much by ciliary action. Mayor (1924*a*) found, however, that *Acropora* was less able to remove fine silt than *Pocillopora*.

Porites.—There was considerable variation in the rate of cleaning between the different colonies. Of the four colonies investigated, one cleaned itself in twenty-four hours on several occasions but the others took two or even three days. The action of the wind in depositing sediment on the coral was noted here also. *Porites* colonies are generally more or less dome-shaped, and the small calices present little holding place for sediment, so that much of the cleaning is probably done by water movement. In an experiment in which various species of coral were exposed in a " live-car " to a rain of sediment, Mayor (1924*c*) found that *Porites* withstood the unfavourable conditions longer than other corals, including species of *Acropora*, *Fungia*, and *Pocillopora*.

In the above experiments, the results are due to the combined effect of wind, tide, and the action of the corals themselves. To exclude the last effect, some experiments were carried out with dead corals. Some corals were cleaned and then painted over with paraffin-wax so as to present a surface more or less like the living coral. Others were fixed in formalin and well washed with sea-water. These prepared corals were then set in positions similar to the living experimental corals, covered with sand as before and the condition noted. The fixed specimens could, of course, only be left out for two or three days since the tissues will gradually disintegrate in the sea. The waxed corals (*Symphyllia* and both types of *Favia*) did not become clean at all in calm weather, but in windy weather they were cleaned more effectively than the living coral.

The fixed corals are probably better from the point of view of the experiments since their surface is more like that of the living corals.

Favia.—In both types very little cleaning took place even in windy weather, which shows that ciliary action is important in the living coral.

Symphyllia recta.—No cleaning was effected in calm weather, but a certain amount of sand was washed out in windy weather. Ciliary action is evidently important here also.

Acropora.—A fixed specimen covered with sand was found clean except at the base after forty-eight hours in windy weather. No conclusions can be drawn from a single experiment, but it is indicated that water movements are important with branching forms.

Porites.—Fixed specimens showed much the same change as living coral, being partially clean after two days in calm weather and quite clean after one day's hard wind. This indicates that with *Porites*, water movements are more important as cleansing agents than is ciliary action.

On the whole the results of these experiments show that the common types of corals, when they are helped by water movements as well as by their own ciliary action, are well able to deal with any ordinary amount of sand falling on them. Details of the nature and direction of beat of the ciliary currents on the polyps and coenosarc of corals which are responsible for the removal of sand have already been given by Yonge in this volume. The amount of sand put on the corals was greatly in excess of anything which would fall under ordinary circumstances but was usually got rid of in at most two or three days. Branching colonies, or those with large polyps, were best able to clean themselves. In cases where the coral, instead of presenting a convex surface, has cracks or hollows in it, sediment does tend to collect, is difficult to remove and may kill off a portion of the coral. These are exceptional cases, however, and are rarely seen except in shallow water.

Several of the corals which were treated with sediment in these experiments were, as has been mentioned, temporarily buried, but by wind, tide, or their own efforts the sand was invariably returned to its natural level. When sand is gaining continuously, however, some corals will be permanently buried, and it is quite common to find in sand patches corals which are living down to sand-level and have recently been alive below sand-level also. These specimens show an abrupt line of separation between living and dead polyps at sand-level. Photographs of such corals, taken by Mr. G. W. Otter, are shown in Plate I (*a*).

Mayer (1918) has recorded the time required to kill different species of corals by burying them, and since this is probably dependent on their resistance to lack of oxygen, it will be governed by the grade and degree of movement of the sand. To find their ability to withstand burial, a number of corals were half buried edgewise in the sand in one of the small coral pools on the flat. *Pocillopora bulbosa*, *Favia* (the small-polyped form), *Fungia danai* and *Porites* were dead below sand-level when examined two and a half days later. There was a sharp line of demarcation at sand-level, all the polyps above this being alive and healthy, all below dead and bleached. *Psammocora gonagra* was dead in parts below the surface, but the large-polyped *Favia* was still alive, although the tissues at and below sand-level were much swollen, usually a sign of distress. By the next day a few polyps had died, and when last examined a few days later it was dead below sand-level, and even at sand level the tissues were swollen.

Sudden burial is, of course, an unlikely phenomenon in nature, and the effect of gradual burial was tried by another method. In this case each coral was put in a sediment collecting jar and two positions were chosen, one in the Western Moat and one in the eastern end of the *Fungia* Moat. The corals exposed were *Favia* (*Goniastrea*) *pectinata*, *Fungia danai*, *Psammocora gonagra* and *Porites*. They were left out for eighteen days and the corals then examined *in situ* and the sediment measured. The fall of sediment was heavy, though it was not equal in all the jars even in one position. The fall was a good deal heavier in the *Fungia* Moat than in the Western Moat. It consisted of a mixture of fine and coarse sand with a little organic detritus. In most cases the sediment at the foot of the jar was beginning to turn black. The area of the corals exposed at the beginning of the experiment was measured and the amount of sediment falling on their surface calculated from this. The level of the sand in the jars was higher on one side than the other, showing the direction from which it had been carried.

Favia.—One specimen was completely buried, while the other showed only a tiny patch bare. The exposed patch had obviously been removing sediment actively, for it lay in a slight depression in the sand. The buried part of both corals was dying. The amount of sediment which fell on them was 56 and 36 gm. respectively.

Fungia danai.—Both specimens had behaved in a most unexpected way (see Plate II, 7, 8, 9). In both jars, the coral was lying on the top of a layer of sand about 6 cm. deep and was perfectly clean. In one case it was lying flat; in the other it was standing against the side of the jar with one edge in the sand. The amount of sediment which had fallen on the corals was 189 and 99 gm. respectively. The evidence of the other jars seems to rule out the possible explanation that local currents have raised the corals, yet it seems unlikely that they can climb through 6 cm. of sand unaided. An attempt was made in the laboratory to repeat this with *Fungia*, but it was unsuccessful, perhaps because it did not last long enough. Sand was sprinkled on a *Fungia* in a finger-bowl through which a gentle stream of sea-water was kept flowing. As soon as the coral had got rid of the sand more was sprinkled on top. On looking at it from below after twenty-four hours the underside of the *Fungia* was seen to be quite bare, *i. e.* none of the sediment had been pushed below it. The *Fungia* stopped removing the sand, and died before the experiment could be carried further.

Psammocora gonagra.—One specimen was completely buried, and the other buried all but the tips of the " leaves." The buried parts were dying. The amount of sediment which had fallen on the corals was 88 and 77 gm. respectively.

Porites.—One specimen was completely buried and the other almost so. The former was dead, and in the latter, even the exposed part had sand lying on it and was unhealthy looking. The amount of sediment which had fallen on the corals was 73 and 54 gm. respectively.

The conclusion to be drawn from these results is that a coral will be killed by sediment up to the level at which it lies in a position of equilibrium. Accidental covering with sand merely results in the combined effects of water movement and the coral itself returning this sand to its original level, as in the first experiments described. When any circumstance interferes with the permanent level for more than a few days, the corals are killed off up to this new level. At many places on the reef flat there is a gradual increase in the amount of sand, and this encroaches on the polyps of the low-living corals and kills them.

Experiments in the Aquarium.

Experimental work on the reef is considerably complicated by a lack of knowledge of the extent to which currents, tides and wave action are responsible for the removal of sediment. For this reason a series of experiments was carried out in the aquarium by exposing coral to different types of sediment. Four common types of coral were chosen, *Favia* (*Goniastrea*) *pectinata*, *Porites*, *Fungia danai* and *Psammocora gonagra*. The first is a colony with large polyps, the second a colony with small polyps, the colonies in both being generally roughly dome-shaped. *Fungia* is a solitary coral with an almost flat surface, and *Psammocora* a branched colonial type with small polyps (see Plate I (*b*), (*c*), (*d*), (*e*)). These corals were chosen partly for their variety of form, and partly because it was known that they were hardy and would live well under aquarium conditions. Small specimens had to be selected, and the base of attachment of colonies of *Favia* and *Porites* was cleaned and freed as far as possible from boring organisms. Corals do not live so well in an aquarium as under natural conditions, as is shown by the fact that several of the control corals died.

The corals were exposed in glass jars 10 cm. in diameter containing one and a quarter litres of water, so that the corals lay under a column of water 15 cm. in height. The water was changed daily about 9 a.m. and the corals were fed every fourth night from a tow-netting rich in small crustaceans.

Three types of sediment were used :

(1) Mud, sieved through standard bolting silk of 80 meshes to the centimetre.

(2) Fine sand, passing square-mesh wire sieve of 2 mm. and washed free from finer material.

(3) Coarse sand passing a wire sieve of 3 mm. square-mesh and stopped by one of 2 mm. square-mesh.

The mud was obtained from a depth of 10 fathoms to the N.W. of Low Isles and the coarse and fine sand were taken from the surface of the sand flat. All were well washed to remove as far as possible any organic material, and only on prolonged standing was there any blackening from this cause. If this precaution had not been taken, it is probable that the corals would have been affected to some degree by the unhealthy conditions caused by the oxidation of the organic matter.

Mud.—Six specimens of each coral were set up; two as controls, two in still water and two in water which was kept in motion to some extent by a plunger. In addition the stirred jars were agitated three or four times a day. In the first experiment a volume of mud (dry weight 0·2 gm.) was added by pipette to the jars containing the coral and the whole well stirred up. When freshly added the mud made the water very cloudy, and on looking from above the coral was hardly visible. This is a condition rarely met with in nature. By next morning the mud in the still water had settled completely and the condition of the corals was noted. The whole was then washed out with fresh sea-water and the experiment re-started on the same corals. This procedure was continued for seven successive days.

Favia.—Individual specimens varied a good deal, but on the whole they managed to clean themselves fairly well. Two specimens, one in still and one in stirred water, died on the third day, but the corals which replaced them cleaned themselves satisfactorily. The coral secretes mucus which entangles the mud and is gradually removed from the calices to the ridges between them. The mud and mucus are then carried along the ridges to be dropped over the edge of the colony. When cleaning was only partly completed, there was a line of mud and mucus along all the ridges.

Fungia.—This coral also cleans itself by entangling the mud in a layer of mucus and gradually sweeping this off its surface by ciliary action, generally from the mouth outwards. In healthy specimens this sheet of mud and mucus would be drawn off completely, leaving the coral quite clean. In specimens not so healthy only a small area was cleaned. The corals in stirred water remained perfectly healthy all the time, those in still water gradually failed to remove the sediment and were unhealthy at the end of the week.

Psammocora.—This coral proved less able to clean itself, although the specimens in stirred water did so a little better than those in still water. Mucus is secreted and the mud and mucus carried off the horizontal surfaces to the edges of the "leaves." Incompletely cleaned specimens were always seen with strings of mud and mucus round the edges of the "leaves."

Porites.—This form is not so successful as *Fungia*. Mucus was secreted and the mud entangled in it, but this was rarely swept right off the surface. After twenty-four hours only small patches were clean on most of the specimens. One coral died during the experiment and two were unhealthy at the end.

Since most of the corals showed that, if healthy, they could deal with this amount of mud daily, the quantity was increased five times, *i. e.* 5 c.c. (1 gm. dry weight) of mud were added daily and the experiment repeated for another seven days. The unhealthy specimens were replaced by fresh.

Favia.—This coral was more successful than in the last experiment and all the colonies used were able to rid themselves of the mud to a large extent.

Fungia.—This coral was also more successful than in the first experiment. Three of the specimens cleaned themselves completely every day, while the fourth generally remained covered by a layer of mud and mucus.

Psammocora.—Here also the coral cleaned itself more effectively than in the previous experiment.

Porites.—This coral did not behave so well as in the previous experiment except for one specimen which cleaned itself completely every day.

On the whole, in these experiments with mud, the corals in stirred water cleaned themselves better than those in still water, but individual variation is so great that this may be the result of chance.

Two experiments were carried out by putting specimens of the four types of coral into a glass tank, adding the usual proportion of mud (1 gm. to $1\frac{1}{4}$ litres), and observing them at frequent intervals.

Favia began to clean itself at once and in the second experiment was completely clean in twenty-four hours, although in the first it was not quite clean till the third day.

Fungia began to clean itself in about two hours but in neither case did it become more than half clean.

Psammocora in the first experiment was almost clean in three days and in the second was partially clean in twenty-four hours.

Porites in the first experiment began to clean itself after eight hours, but even after three days was only clean in patches. In the second experiment it did not clean itself at all.

In general it may be said that a healthy coral can rid itself of even the larger amount of mud but individual specimens vary greatly. *Favia* and *Fungia* appear to be most capable of dealing with the sediment and *Porites* least so. The method of removal is the same in all cases, the secretion of mucus entangling the mud and its removal by ciliary action.

Somewhat similar observations under natural conditions have been made by Mayor (1924*a*). He found that much greater dilutions of mud (3·7 gm. per 100 litres) were fatal to various corals. There was, however, at the same time a considerable lowering of the salinity, which would also have an injurious effect (Mayer, 1918).

Fine Sand.—Another experiment was carried out in the same way as the first two, using fine sand instead of mud. The experiment lasted as usual for seven days. About 40 gm. of sand was put in daily and scattered as evenly as possible over the coral. The sand was too heavy to be kept in motion by the plunger, so, for each of the four genera, there were two controls and four experimental corals.

Favia.—As before, the coral showed itself able to deal with the sediment. All the specimens were as healthy at the end as at the beginning, and were in fact getting rid of the sand more completely during the last few days.

Fungia.—A healthy specimen can remove this quantity of sand at first, but it gradually weakens, and after seven days all the specimens were in an unhealthy or dying condition.

Psammocora.—All specimens failed to get rid of the sand.

Porites also showed itself unable to deal with the sand. One specimen succeeded in cleaning itself once, but as a rule the sand remained on the top of the coral where it had fallen.

The amount of sand put into the water daily gives only a rough idea of the amount actually coming to rest on the coral. In the case of *Porites* whose surface is convex most of the grains falling on the surface rolled off again at once, leaving only little collections on the top or in the hollows. The same was the case with *Favia*, although here the larger calices were more apt to hold the grains. In both cases these corals under natural conditions must be cleaned partly by the action of wave and tide movements (see pp. 124, 125). Since *Fungia* is a flat coral, the sand falling on the surface stayed there and had all to be removed by ciliary action. In the case of *Psammocora* a good deal of sand was held up in the angles of the " leaves." As has already been mentioned, *Psammocora* was very slow in cleaning itself even on the reef flat, and judging from its inability to do so in the aquarium, it must depend on water movements almost entirely. Yonge, however, found that, when observed under a binocular microscope, the ciliation is very efficient.

A series of photographs was taken for us by Miss S. M. Manton and Mr. M. A. Spender of a single specimen of *Fungia* and *Favia* removing fine sand. The coral was put in a glass finger-bowl and the usual quantity of fine sand scattered carefully over the surface. It was kept out of doors, shaded from the direct sunlight except when the photographs were actually being taken and photographed at intervals during the day and once next morning. These photographs are shown in Plates II (1–6) and III. Although it does not show well in the photographs, the sand pushed off the coral remains as a ridge round its edge.

Coarse Sand.—The last experiment was carried out as before with the corals in glass jars, using the coarse sand and adding 40 gm. daily for nine days.

Favia got rid of the sand most successfully. There were often a few grains in some of the calices on the top of the colony, but the greater part of it was quite free of sand by next morning.

Fungia.—Healthy specimens could get rid of the sand for at least one or two days, but their capacity gradually decreased, and at the end of seven days they were dying or unhealthy. Small specimens, which were often buried completely by the amount of sand added, could only clean a small part of themselves.

Psammocora and *Porites* proved as incapable of dealing with coarse as with fine sand. Only on a single occasion did one *Porites* manage to clean itself at all.

Since sand is heavier than mud, it might be expected that the corals with small polyps would find it more difficult to remove than mud, and this is the case. *Porites* and *Psammocora* rarely make any attempt to clean themselves. *Favia* removes sand as easily as mud. *Fungia* can remove it also but, at least in the laboratory, the effort weakens it and the coral dies at the end of a week. Mucus is much less apparent than when they were dealing with mud.

Discussion.

While, on the whole, corals are able to rid themselves of large amounts of sediment, it is clear that some species are much more sensitive than others, and that continued exposure to sediment has, at least in the laboratory, a harmful effect. As a rule, corals with large polyps are more efficient than corals with small polyps unless the latter are finely branched. It has already been shown by Yonge that the ciliary currents of many small-polyped corals assist in feeding, and that their efficiency as cleansing mechanisms is impaired to a greater or less degree as a result. When a large-polyped form such as *Favia* or *Symphyllia* expands at night, the polyp rises to some distance off the skeleton and this must help to throw off the sediment. The corals used in the laboratory were not often fully expanded, and so this factor was not of much importance in the laboratory experiments. The removal of sediment takes place more easily in the sea, for the coral is then aided by natural water movements.

In the sea, as in the laboratory, *Porites* is the least efficient of the corals tried and seems to depend almost entirely on water movements. On the reef there are often found colonies which are flat-topped and dead in the centre. In the moat at Low Isles the tops of all the flat-topped *Porites* occurred at almost the same level, namely just above the constant low tide level, which indicates that they have been killed by exposure to unfavourable conditions at low tide. This is confirmed by the fact that such flat tops are seldom, if ever, found in deep water at Low Isles. The condition has been noted by Wood-Jones (1912) and others, but has generally been ascribed to killing off by sediment. Wood-Jones mentions some *Porites* colonies of this type which are below low tide level. In some cases, too, there is a living healthy mass growing on the top of a dead centre. It is possible that both exposure and sedimentation may bring about this condition, but on Low Isles the effect of exposure at low tide is certainly predominant.

The same remarks apply to the dead flat tops of *Favia* colonies, although here it is still more difficult to believe that sedimentation can have caused death when we consider how much sand can normally be removed by this coral.

Fungia, as was recognized by Wood-Jones (1912), is exceptional in its ability to remove sediment. Normally it lies flat on a sandy or muddy bottom and is exposed to a considerable rain of sediment. *Psammocora* is a very hardy coral and will stand a large amount of exposure. Being a small-polyped form, it depends to a large extent on water movements for the removal of sediment. The main danger for this type of colony seems to be the danger of silting up from below.

The other corals investigated, *Pocillopora*, *Galaxea*, *Symphyllia*, *Fungia* and *Acropora* were all able to deal with large quantities of sediment under natural conditions, and it is difficult to believe that they can be killed by sediment falling from above. Experiments on the burial of coral are a different matter ; these really test the ability of the animal to withstand lack of oxygen and this is not great. It has often been stated that coral reefs have been exterminated by an increase in the amount of sediment, but it must be inferred that this sediment has acted by silting up the whole mass of the colonies.

A change of bottom level, if it lasts for more than a day or two, effectually kills all the polyps which are covered. Such changes of level are constantly taking place by the movement of sediment on the reef flat during windy weather.

If it is true that sediment falling from above does not seriously affect corals, then Wood-Jones's explanation of the fact that reef-building corals do not flourish below 60–80 metres will not hold. He thinks that it is because they are below the depth at which there are currents capable of carrying sediment in suspension and that they are therefore subjected to a constant rain of it. The amount of sediment falling normally on a coral reef at a depth of 60 metres must be small indeed compared with the amounts which we added to our corals, and, except in the case of small-polyped colonies with large exposed surfaces, it is probable that they could deal with it easily.

Conclusions.

Corals can and do live in slightly turbid waters, and for a limited period can withstand large quantities of sediment falling from above. Water movements and the ciliary action of the corals themselves are the effective agents in removing sediment. Sediment coming from below kills in a day or two all the polyps thus covered.

We wish to thank various members of the Expedition for their assistance, especially Mr. A. G. Nicholls, without whose constant help this work could not have been carried out.

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INDEX

DESCRIPTION OF PLATE I.

(*a*) Coral colonies which have been killed by silting up from below. There is a sharp line of demarcation between the living colony above and the dead colony below sand-level.

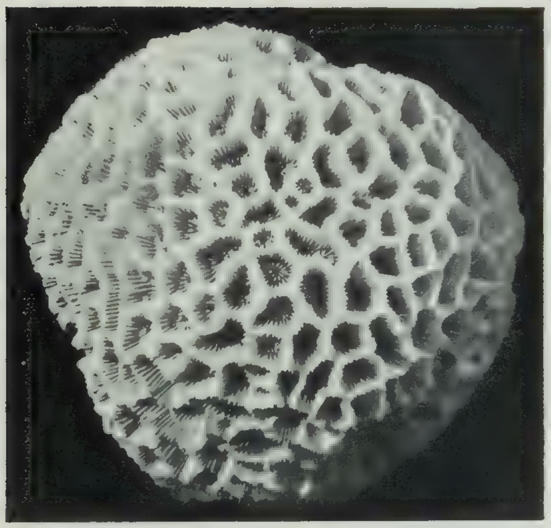
(*b*) *Favia (Goniastraea) pectinata* used in experimental work in aquarium.

(*c*) *Porites* used in experimental work.

(*d*) *Fungia danai* used in experimental work.

(*e*) *Psammocora gonagra* used in experimental work.

a.



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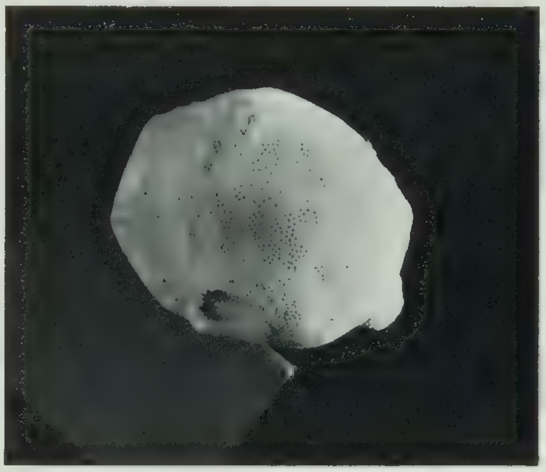

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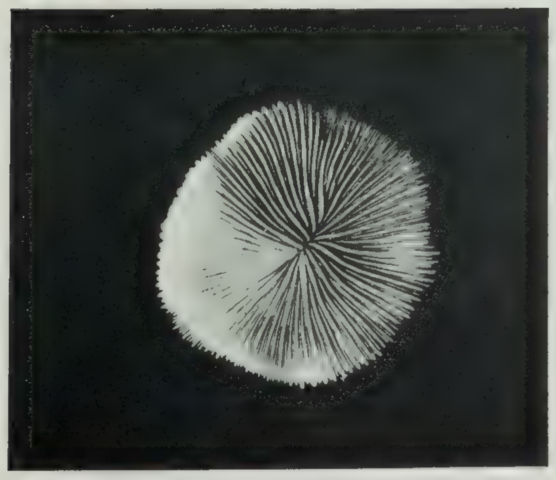

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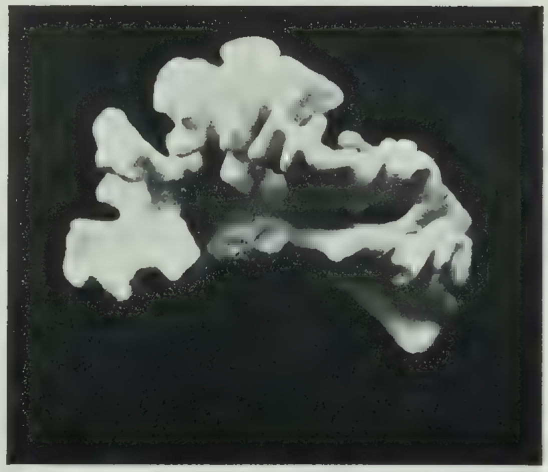

e.

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DESCRIPTION OF PLATE II.

(1)-(6) *Favia* (*Goniastraea*) *pectinata* cleaning itself from fine sand.

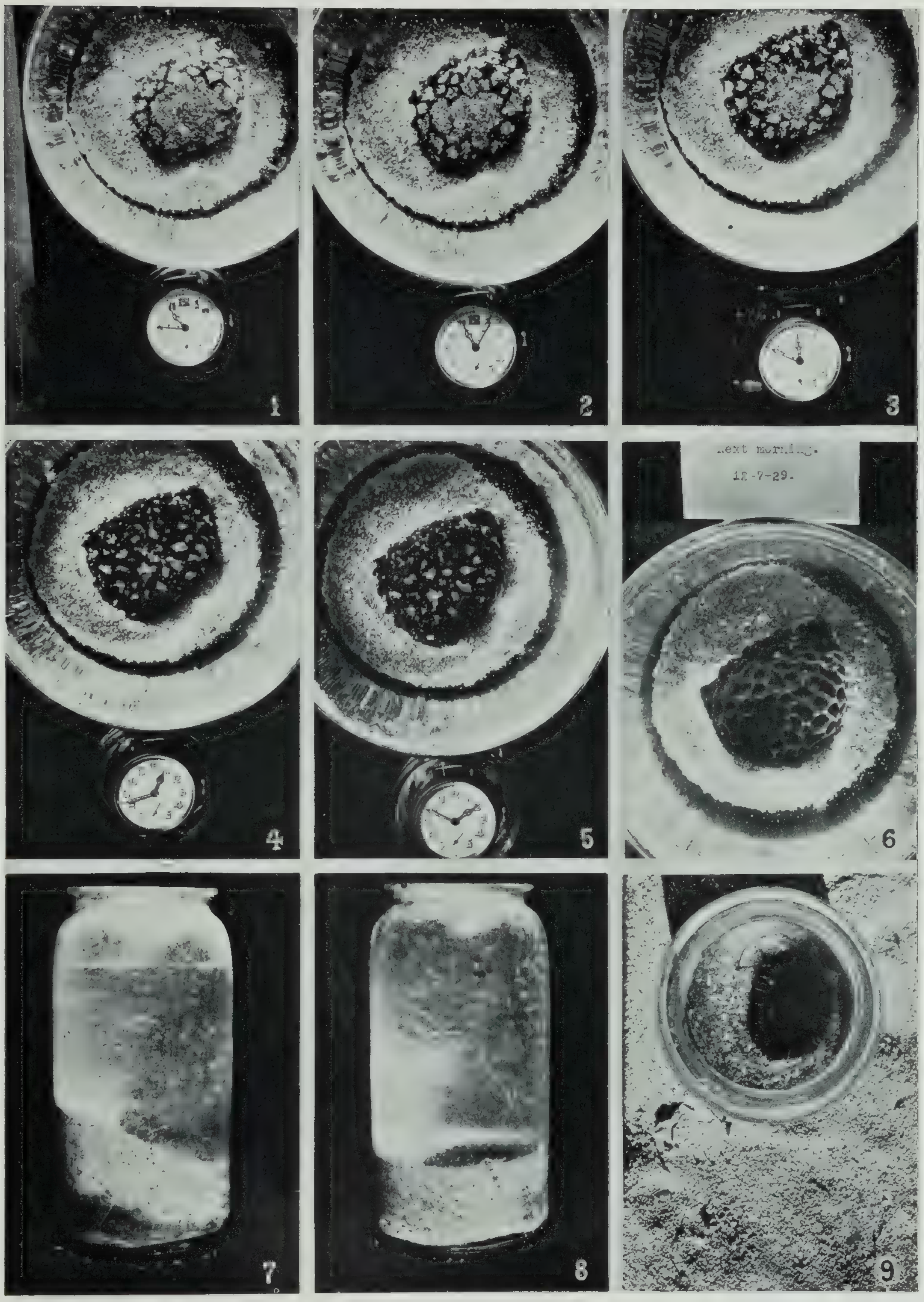
(7) *Fungia danai* as it appeared after eighteen days' exposure to sedimentation on the flat.

(8) Another specimen exposed in the same way as (7).

(9) (8) from above to show the surface of the *Fungia* free from sediment.

(7), (8) and (9) show sediment-collecting jars.

(7) Shows typical blackening at the bottom of the sediment in the jar.



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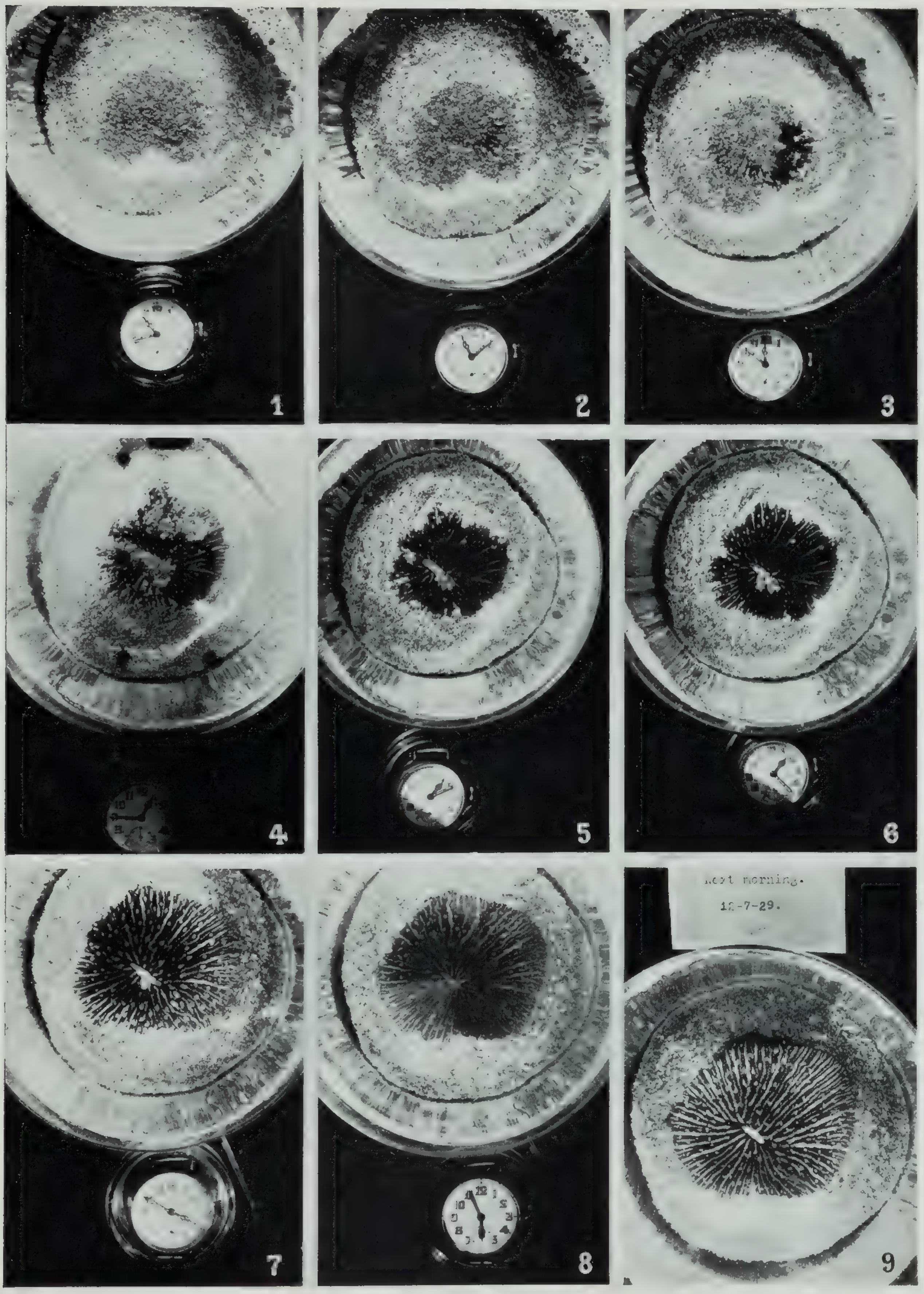
DESCRIPTION OF PLATE III.

Fungia danai cleaning itself from fine sand.



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